

RAPORT KOŃCOWY Z REALIZACJI CZĘŚCI ZADANIA BADAWCZEGO

3. Zwiększenie wykorzystania energii z odnawialnych źródeł energii w budownictwie

w ramach strategicznego programu badań naukowych i
prac rozwojowych strategicznego projektu badawczego

Zintegrowany system zmniejszenia eksploatacyjnej energochłonności Budynków

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Etap nr 8: Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej

Celem przeprowadzanych badań w Etapie 8 jest opracowanie modelu matematycznego służącego do analizy systemowej gospodarki energetycznej kompleksu budowlanego użyteczności publicznej. W pierwszej kolejności dokonano przeglądu bazy wiedzy dotyczącej współczesnych urządzeń i systemów energetycznych stosowanych w kompleksach budowlanych użyteczności publicznej. Szczególnej analizie poddano rozwiązania energetyczne wykorzystujące odnawialne źródła energii. Skompletowano bazę wiedzy o ich wskaźnikach energetycznych i ekologicznych. Następnie bazując na teorii przepływów międzygałęziowych opracowano modele matematyczne bilansu bezpośredniego oraz skumulowanego zużycia energii. Bazując na opracowanej metodyce stworzono model matematyczny skumulowanej emisji substancji szkodliwych do otoczenia. W modelach matematycznych uwzględniono możliwość wykorzystania nośników energii ze źródeł odnawialnych.

1. Opracowanie bazy wiedzy na temat urządzeń energetycznych wytwarzania ciepła, elektryczności i chłodu w budynkach użyteczności publicznej oraz możliwości zastosowania w nich odnawialnych źródeł energii

1.1. Wprowadzenie

Współczesne budynki użyteczności publicznej charakteryzują się szczególnie złożoną strukturą gospodarki energetycznej. Spowodowane to jest coraz powszechniejszym zastosowaniem różnego rodzaju wariantów instalacji ogrzewania, chłodzenia, wentylacji i klimatyzacji, a w przypadku kogeneracji również zasilania w energię elektryczną. Stwarza to określone możliwości wykorzystania odnawialnych źródeł energii w tego typu budynkach. Coraz częściej stosowane są układy realizujące gospodarkę skojarzoną polegającą na równoczesnym wytwarzaniu ciepła i elektryczności. Są to zarówno tradycyjne układy silnikowe tłokowe lub turbinowe, jak również układy skojarzone oparte na ogniwach paliwowych. W ostatnich latach dużą uwagę przywiązuje się do układów kogeneracyjnych wykorzystujących silniki Stirlinga. Układy takie mogą być zasilane biomasą spalaną bezpośrednio bądź uprzednio poddaną zgazowaniu. W tego typu układach z powodzeniem mogą zostać zastosowane również inne paliwa odnawialne np. biogaz czy płynne paliwa pochodzenia roślinnego. Pewne możliwości wykorzystania odnawialnych źródeł energii w budynkach użyteczności publicznej stwarza również technologia ORC (Organic Rankine Cycle). Przez zintegrowanie układów skojarzonych cieplno-elektrycznych z urządzeniami ziębniczymi możliwe jest równoczesne wytwarzanie ciepła, elektryczności i chłodu w jednym układzie. Są to tzw. układy „trigeneration”. W ramach przeprowadzonych badań stworzono bazę wiedzy na temat urządzeń energetycznych wytwarzania ciepła, elektryczności i chłodu w budynkach użyteczności publicznej oraz możliwości zastosowania w nich odnawialnych źródeł energii.

Sektor budowlany należy do głównych odbiorców energii pierwotnej. Stanowi to ok. 40% całkowitego zużycia energii pierwotnej w danym kraju i wartość ta ma tendencję rosnącą w wyniku rozwoju tego sektora. Użytkowanie energii w budynkach jest ściśle związane z powstawaniem zanieczyszczeń i ich negatywnym oddziaływaniem na środowisko naturalne. Dążenie do zmniejszenia zużycia energii w budynkach stanowi więc istotne zagadnienie z punktu widzenia wyczerpywania zasobów nieodnawialnych bogactw naturalnych. Dlatego w planowaniu gospodarki energetycznej nowych budynków należy poszukiwać rozwiązań prowadzących do minimalizacji zużycia nieodnawialnych źródeł energii, biorąc pod uwagę

warunki klimatyczne oraz lokalne wymagania użytkowników. Znaczny potencjał zmniejszenia zużycia energii istnieje również w racjonalizacji gospodarki energetycznej istniejących budynków. Współczesne kompleksy budowlane takie jak: biurowce, szpitale, centra handlowe, galerie, porty lotnicze, itp. wymagają szerokiej gamy nośników energii w celu zapewnienia komfortu cieplnego oraz pokrycia potrzeb technologicznych kompleksu budowlanego. Rosnące standardy dotyczące racjonalnego użytkowania energii oraz związane z zapewnieniem komfortu wewnętrznego prowadzą do wprowadzania nowych urządzeń i układów energetycznych w kompleksach budowlanych.

Ciepło i energia elektryczna są podstawowymi nośnikami energii finalnej zużywanymi w kompleksach budowlanych. Dlatego z ekonomicznego i ekologicznego punktu widzenia wytwarzanie tych nośników powinno być realizowane w efektywny sposób. Jedną z najbardziej efektywnych technologii konwersji paliwa do formy przekazywania energii w postaci ciepła i elektryczności jest wytwarzanie tych nośników energii w skojarzeniu (tzw. kogeneracja). Stosowane w budynkach układy kogeneracyjne małej mocy bazujące na tłokowych silnikach spalinowych i turbinach gazowych to tzw. układy CHP –ang. Combined Heat and Power. Energia elektryczna generowana w prądnicy układu CHP może być w całości zagospodarowana w budynku, bądź w części sprzedana do sieci lub innemu odbiorcy zewnętrznemu.

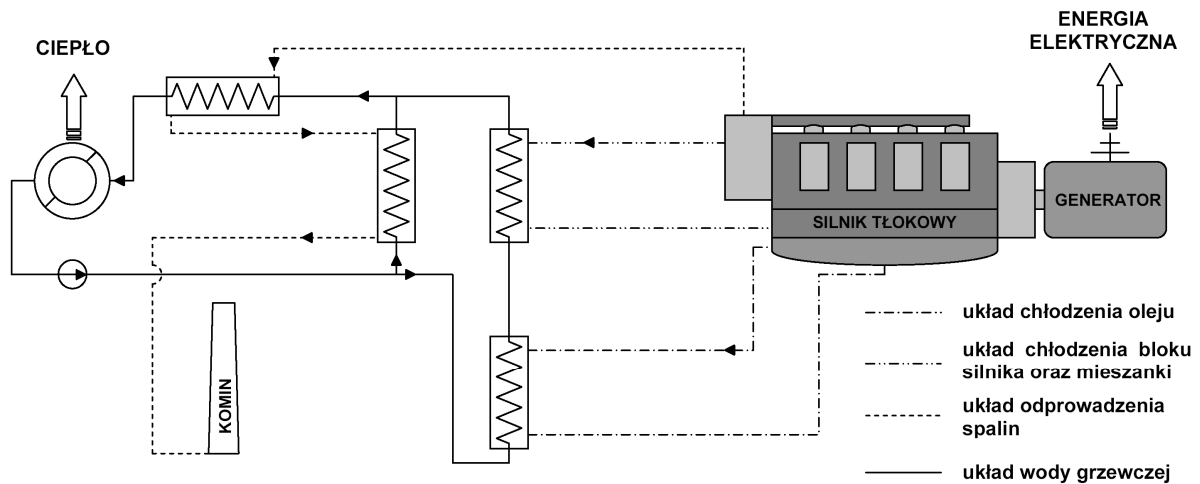
Coraz częściej dokumenty UE (w tym Dyrektywa 2002/91/EC) określają zastosowanie układów CHP w budynkach jako priorytetową technologię prowadzącą do zmniejszenia zużycia nieodnawialnych bogactw naturalnych oraz redukcji negatywnego oddziaływania budynków na środowisko naturalne.

Aby układ skojarzony mógł być efektywnie wykorzystywany w kompleksach budowlanych, niezbędne jest występowanie przez określoną liczbę godzin w roku równoczesnego zapotrzebowania na ciepło i elektryczność. Spełnienie tego kryterium decyduje o tym, czy inwestycja ta osiągnie dodatni efekt ekonomiczny, wynikający z zastąpienia ciepła pochodzącego z sieci ciepłowniczej lub wytwarzanego lokalnie w kotłach oraz elektryczności dostarczanej z sieci przez ciepło i elektryczność wytwarzane w układzie skojarzonym zainstalowanym w kompleksie budowlanym.

1.2. Układy kogeneracyjne z silnikami tłokowymi

Podstawową grupą układów CHP stosowanych w nowoczesnych kompleksach budowlanych stanowią układy bazujące na tłokowych silnikach spalinowych. Silnik tłokowy takiego układu napędza generator asynchroniczny lub synchroniczny, a ciepło

wytwarzane jest w układach chłodzenia silnika. Takie rozwiązania znajdują najczęściej zastosowanie do produkcji gorącej wody. Na rysunku 1.1 przedstawiono schemat przykładowego układu CHP opartego na tłokowym silniku spalinowym.



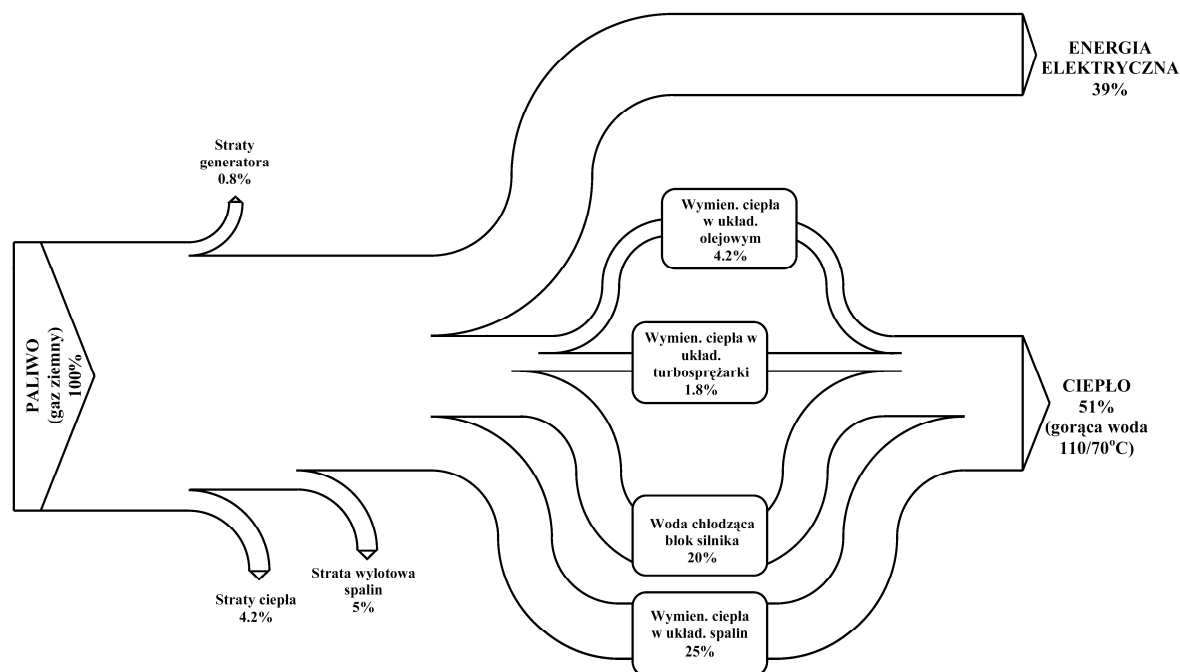
Rys. 1.1. Schemat przykładowego układu CHP z silnikiem tłokowym

Układy CHP z silnikami tłokowymi dostępne są obecnie na rynku w szerokim zakresie mocy (począwszy od kilku kW). W tabelicy 1.1. przedstawiono parametry kilku dostępnych komercyjnie rozwiązań tego typu. Odbiór ciepła odbywa się najczęściej z kilku układów chłodzenia silnika, na różnych poziomach temperaturowych. Największa ilość ciepła jest produkowana przez układ chłodzenia płaszcza wodnego silnika oraz przez obieg oleju smarowego. Ciepło jest odzyskiwane również z mieszanki doładowania za turbosprężarką oraz ze spalin. Ilość produkowanego ciepła w układzie chłodzenia silnika (chłodzenie bloku silnika, oleju smarowego i mieszanki doładowanej) w odniesieniu do strumienia energii chemicznej paliwa wynosi około 30%. Wytwarzany w ten sposób czynnik jakim jest gorąca woda posiada temperaturę około 85-90°C i jest najczęściej wykorzystywany na cele grzewcze oraz do produkcji ciepłej wody użytkowej. Gorąca woda produkowana w układzie chłodzenia spalin (wymiennik ciepła spaliny-woda) posiada wyższą temperaturę, około 100-120°C. Ciepło wytwarzane w tym układzie stanowi około 25-30% dostarczanego strumienia energii chemicznej. Za wymiennikiem spaliny-woda gazy wylotowe posiadają temperaturę około 120°C. Dalsze obniżenie temperatury spalin jest możliwe przy zastosowaniu kondensacyjnego wymiennika ciepła. Takie rozwiązanie wiąże się jednak z poniesieniem kosztów na dodatkowy wymiennik. Jest to w pełni uzasadnione, gdy w budynku istnieje zapotrzebowanie na czynnik grzewczy o niskiej temperaturze np. w przypadku zastosowania ogrzewania podłogowego lub wytwarzania ciepłej wody użytkowej. Na rys.

1.2 przedstawiono wykres pasmowy bilansu energii w typowym układzie CHP z silnikiem tłokowym.

Tablica 1.1. Parametry komercyjnie dostępnych układów CHP bazujących na tłokowym silniku spalinowym

	Układ 1	Układ 2	Układ 3	Układ 4	Układ 5
Moc elektryczna, kW	43	100	526	1063	5005
Sprawność wytwarzania energii elektrycznej, %	33.3	34.1	39.5	40.8	41.4
Moc cieplna, kW	72	167	635	1190	6355
Wskaźnik skojarzenia	0.6	0.6	0.83	0.89	0.79
Sprawność całkowita, %	89.1	90.1	87.1	86.4	94



Rys. 1.2. Wykres pasmowy bilansu energii w przykładowym układzie CHP z zastosowaniem tłokowego silnika spalinowego

1.3. Układy kogeneracyjne bazujące na mikroturbinach gazowych

Kolejnym sposobem realizacji gospodarki skojarzonej w kompleksach budowlanych jest zastosowanie mikroturbin gazowych w układach CHP. W odróżnieniu od układu opartego o silnik tłokowy układ z turbiną gazową charakteryzuje się znacznie większym stosunkiem mocy do masy oraz niższym poziomem emisji hałasu i drgań. Porównując układy w niektórych zakresach mocy, układ z turbiną gazową bywa nawet dziesięciokrotnie lżejszy

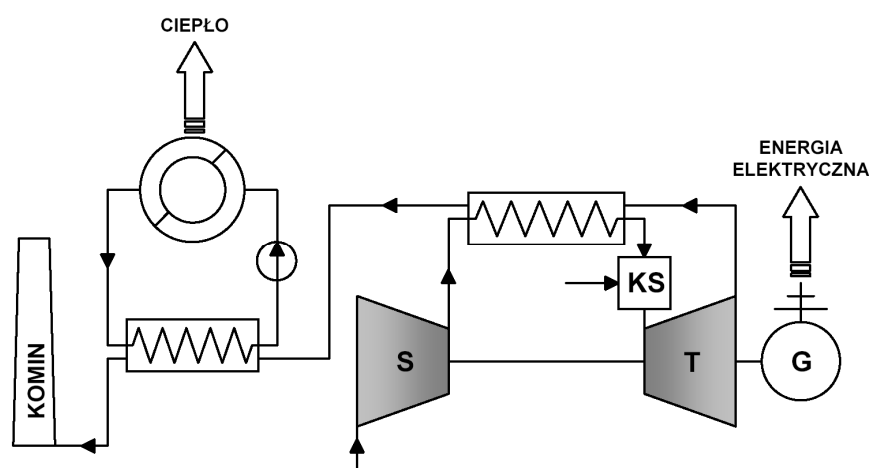
od jednostki bazującej na spalinowym silniku tłokowym. Układ turbinowy nie posiada układu chłodzącego, a jedynym źródłem ciepła pozyskiwanego z układu jest entalpia spalin wylotowych.

W ostatnim okresie mikroturbiny zyskały opinię dojrzałej technologii i coraz częściej znajdują zastosowanie w celu zaspokojenia potrzeb energetycznych kompleksów budowlanych. Nowoczesne mikroturbiny charakteryzują się stosunkowo prostą konstrukcją dzięki czemu osiągają lepsze wskaźniki dyspozycyjności niż tłokowe silniki spalinowe. Najczęściej są to dwustopniowe jednostki z wirnikiem promieniowym. Obecnie na rynku dostępne są zasadniczo dwa rodzaje mikroturbin: z odzyskiem lub bez odzysku ciepła. W mikroturbinach bez odzysku ciepła sprężona mieszanka gazu ziemnego i powietrza jest spalana w komorze spalania, a uzyskany strumień gorących spalin rozpręża się w turbinie napędzając generator. Turbiny te realizują prosty cykl termodynamiczny, charakteryzują się większą niezawodnością i niższą ceną niż mikroturbiny z odzyskiem ciepła. Mikroturbiny z odzyskiem ciepła posiadają wymiennik regeneracyjny, w którym część ciepła ze spalin wylotowych podgrzewa powietrze dolotowe. Zastosowanie wymiennika regeneracyjnego pozwala na znaczne zwiększenie sprawności wytwarzania energii elektrycznej mikroturbiny. Sprawność współczesnych mikroturbin wykorzystywanych w małych układach CHP jest porównywalna ze sprawnością osiąganą w turbinach większych mocy. Produkowane obecnie mikroturbiny osiągają sprawność produkcji energii elektrycznej rzędu 32% (przy mocy około 300 kW). Przewiduje się, że w niedalekiej przyszłości sprawność elektryczna najlepszych mikroturbin osiągnie poziom 35%. Kilka przykładowych, obecnie komercyjnie dostępnych jednostek CHP bazujących na turbinie gazowej zestawiono w tabelicy 1.2.

Tablica 1.2. Parametry komercyjnie dostępnych układów CHP bazujących na mikroturbinie gazowej

	Układ 1	Układ 2	Układ 3	Układ 4	Układ 5
Moc elektryczna, kW	65	80	100	100	350
Sprawność wytwarzania energii elektrycznej, %	28.8	25.7	30	27.6	32.1
Strumień ciepła, kW	120	150	155	172	582
Wskaźnik skojarzenia	0.54	0.53	0.65	0.58	0.6
Sprawność całkowita, %	0.82	0.74	77	0.75	0.86

W przypadku zastosowania regeneracji ciepła spaliny wylotowe posiadają stosunkowo niską temperaturę. W obecnie produkowanych jednostkach temperatura spalin za mikroturbiną (z regeneracją ciepła) wynosi około 270°C . Po przejściu przez wymiennik ciepła, gdzie produkowana jest gorąca woda spaliny posiadają temperaturę około 95°C . Ciepło ze spalin poprzez układ wodny ($90/70^{\circ}\text{C}$), zintegrowany z modułem CHP, odprowadzane jest do instalacji grzewczej i wykorzystywane jako ciepło użytkowe lub dla procesów technologicznych w budynku. Schemat takiego układu pokazano na rys. 1.3.

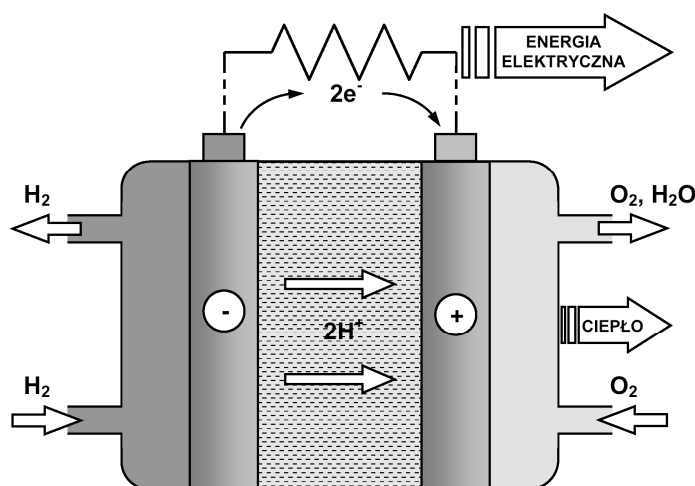


Rys. 1.3. Układ CHP oparty na mikroturbinie gazowej z regeneracyjnym wymiennikiem ciepła

1.4. Układy kogeneracyjne z wykorzystaniem ogni paliwowych

Możliwość realizacji gospodarki skojarzonej w kompleksach budowlanych oprócz układów CHP bazujących na turbinie gazowej lub silniku tłokowym mogą zapewnić również kogeneracyjne układy z ogniwami paliwowymi. Korzenie technologii ogni paliwowych sięgają jeszcze XIX wieku, niemniej jednak pierwsze komercyjne ogniwa paliwowe pojawiły się dopiero na początku lat 90. Ogniwa paliwowe nie są jeszcze co prawda produkowane na szeroką skalę, lecz ich charakterystyczne zalety mogą przesądzić o ich przyszłym, szerokim zastosowaniu. Obecnie na świecie istnieje zaledwie kilku producentów oferujących komercyjne jednostki na potrzeby kompleksów budowlanych. Mimo to zainteresowanie tą technologią jest znaczne, czego dowodem są powstające na całym świecie jednostki demonstracyjne. Wykorzystanie ogni paliwowych w układach skojarzonych jest postrzegane jako niezawodna, przyjazna środowisku technologia realizująca założenia energetyki rozproszonej.

W ogniwach paliwowych następuje bezpośrednia konwersja energii chemicznej paliwa (wodór, gaz ziemny, metanol, itp.) w elektryczność. Przemiana ta odbywa się bez wysokotemperaturowego spalania, a produktem całego procesu jest prąd stały, ciepło oraz woda. W pojedynczym ogniwie znajdują się dwie elektrody w postaci anody i katody. Elektrody te umieszczone są w elektrolicie pozwalającym na przepływ jonów. Do anody doprowadzane jest paliwo np. wodór, natomiast do katody dostarcza się utleniacz np. tlen. Wodór dostarczany jest w postaci czystej bądź jest wytwarzany w procesie reformingu z paliw węglowodorowych. Reforming może zachodzić w zewnętrznym urządzeniu (reformer) bądź w samym ogniwie paliwowym (reforming wewnętrzny). Wskutek procesów elektrochemicznych w ogniwie paliwowym następuje przepływ elektronów oraz jonów od anody do katody. Elektrony przepływają przez obwód zewnętrzny generując w nim energię elektryczną. Jony wodoru przemieszczają się natomiast poprzez elektrolit, następnie wraz z elektronami reagują z tlenem w wyniku czego powstaje woda. Taki sposób realizacji procesu utleniania paliwa sprawia, iż produkcja elektryczności w ogniwie paliwowym nie podlega ograniczeniu wynikającemu z obiegu Carnota. Dzięki temu teoretyczna sprawność wytwarzania energii elektrycznej w ogniwie paliwowym wynosi 100%. Sprawność rzeczywista tego typu układów jest mniejsza z uwagi na straty energii występujące w poszczególnych podzespołach ogniwa. Ideowy schemat ogniwa paliwowego przedstawiono na rys. 1.4.



Rys. 1.4. Uproszczony schemat ogniwa paliwowego wodorowego

Powstałe wskutek procesu ciepło może zostać z powodzeniem wykorzystane w układzie CHP, podobnie jak ciepło z silnika tłokowego czy turbiny gazowej. Zaletami układów CHP bazującymi na ogniwach paliwowych są: niewielka liczba części ruchomych,

praca przy niskim poziomie hałasu i drgań, wysoka sprawność wytwarzania energii elektrycznej (wyższa o ponad 10 pkt.% niż w przypadku układów bazujących na silnikach tłokowych czy mikroturbinach gazowych), dobra regulacyjność, możliwość dużych przeciążeń chwilowych oraz pracy z niskim obciążeniem, jak również niewielka emisja zanieczyszczeń.

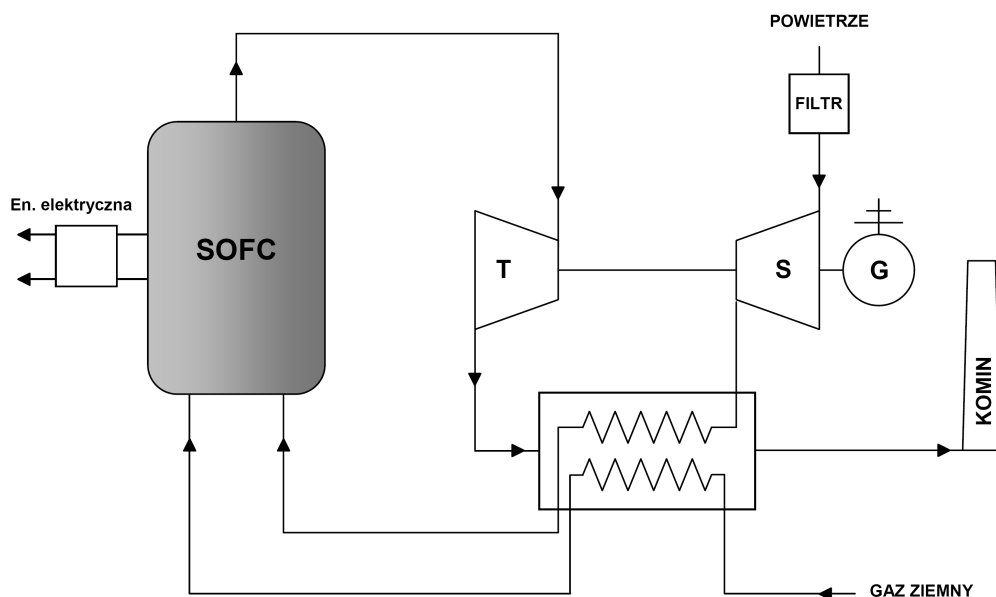
Ze względu na rodzaj zastosowanego elektrolitu można wyróżnić kilka typów ogniw paliwowych. Alkaliczne ogniwa paliwowe (ang. Alkaline Fuel Cell) – ACF wykorzystują elektrolit w postaci tkaniny nasączonej wodorotlenkiem potasu (KOH). Temperatura pracy ogniw zależy od stężenia KOH i mieści się w zakresie 60-100°C. Wadą ogniw ACF jest ich wrażliwość na obecność CO, który "zatrzuwa" katalizator oraz na CO₂, który reaguje z elektrolitem (KOH). Ogniwa tego typu muszą być zasilane czystym wodorem i tlenem, co w znacznym stopniu ogranicza możliwości zastosowania ich w kompleksach budowlanych. Jednostki tego typu charakteryzują się również stosunkowo niskimi mocami. Ogniwa, w których zastosowano półprzepuszczalną membranę pełniącą rolę elektrolitu nazywane są ogniwami typu PEMFC (ang. Proton Exchange Membrane Fuel Cell). Układy te są produkowane w stosunkowo dużym zakresie mocy (5-250 kW_{el}). Ogniwa typu PEMFC należą do grupy ogniw niskotemperaturowych. Pracują w temperaturach rzędu 60-120°C, a ich sprawność waha się w przedziale 35-46%. Ogniwa te, podobnie jak ogniwa ACF wymagają paliwa i utleniacza o wysokiej czystości. Praca tego typu ogniw wymaga źródła ciepła do procesu reformingu paliwa. Ogniwami odpornymi na zanieczyszczenia paliwa są ogniwa PAFC (ang. Phosphoric Acid Fuel Cell) co sprawia, że nadają się one do utylizacji różnego rodzaju paliw gazowych. W ogniwach tego typu jako elektrolit wykorzystuje się kwas fosforowy. Zakres temperatury pracy wynosi 150-220°C, a sprawności elektryczne mieszczą się w przedziale 35-44%. Ogniwa PAFC są najczęściej produkowane w zakresie mocy 200-1000 kW_{el} i z technicznego punktu widzenia dobrze sprawdzają się w układach CHP instalowanych w kompleksach budowlanych. Ogniwami pracującymi w znacznie wyższych temperaturach są ogniwa MCFC. Wysoka temperatura pracy (600-700°C) pozwala na przebieg procesu reformingu w samym ogniwie, bez konieczności instalowania oddzielnego reformera. Podobnie jak ogniwa PAFC, ogniwa te są odporne na obecność innych gazów w mieszance paliwowej i w utleniaczu. Generatory MCFC charakteryzują się stosunkowo wysokimi sprawnościami produkcji energii elektrycznej, rzędu 45-56%. Największe jednostki tego typu posiadają moc ok. 2 MW niemniej jednak najczęściej budowane są w zakresie mocy 200-250 kW. W stosunku do pozostałych typów ogniw

paliwowych odznaczają się stosunkowo niskimi kosztami produkcji. Ogniwami paliwowymi posiadającymi najwyższą temperaturę pracy (rzędu 700-1000°C) są ogniwa stałotlenkowe -SOFC (ang. Solid-Oxide Fuel Cell). W przypadku tego rodzaju ogniw elektrolitem jest warstwa ceramiczna z tlenku cyrkonu (ZrO_2) wzbogaconego itrem (Y_2O_3). Wysoka temperatura pracy pozwala na osiągnięcie stosunkowo wysokich sprawności (w przedziale 44-55%) oraz realizację procesu wewnętrznego reformingu. Podobnie jak agregaty MCFC ogniwa stałotlenkowe mogą pracować przy zasilaniu gazami zawierającymi CO. Podstawowe dane dotyczące poszczególnych rodzajów ogniw paliwowych zestawiono w tablicy 1.3.

Tablica 1.3. Zestawienie parametrów poszczególnych typów ogniw paliwowych

	Zakres mocy, kW	Temperatura pracy, °C	Elektrolit	Reforming	Sprawność wytwarzania energii elektrycznej, %	Sprawność całkowita (wykorzystanie ogniwa w układzie CHP), %
ACF	<100	60-100	Zasada potasowa (KOH)	-	60-65	-
PEMFC	<250	60-120	Membrana półprzepuszczalna	zewnątrzny	35-46	60
PAFC	<1000 (najczęściej ok. 200)	150-220	Kwas fosforowy	zewnątrzny	35-44	80
MCFC	<2000 (najczęściej ok. 250)	600-700	Li_2CO_3/K_2CO_3	zewnątrzny/ we-wnętrzny	45-56	85
SOFC	<3000 (najczęściej ok. 200)	700-1000	Y_2O_3/ZrO_2	zewnątrzny/ we-wnętrzny	44-55	85

Oprócz tradycyjnego wykorzystania ogniw paliwowych w jednostkach kogeneracyjnych produkujących energię elektryczną i ciepło, najnowsze koncepcje przewidują ich zastosowanie w układach hybrydowych z mikroturbinami gazowymi. Układy tego typu nie są jeszcze dostępne na szeroką skalę, lecz fakt powstawania coraz liczniejszych jednostek demonstracyjnych może wskazywać na szersze zastosowanie tej technologii w przyszłości. Układy tego typu charakteryzują się znaczną sprawnością produkcji energii elektrycznej, która w przypadku jednostek małej mocy wynosi ponad 70%, a dla układów większych mocy osiąga wartości nawet powyżej 75%. Najczęściej układy hybrydowe są budowane w oparciu o ogniwa stałotlenkowe (SOFC). Schemat przykładowego rozwiązania tego typu przedstawiono na rys. 1.5.



Rys. 1.5. Hybrydowy układ małej mocy wykorzystujący stałotlenkowe ogniwo paliwowe oraz mikroturbinę gazową

W tabelicy 1.4 zestawiono cechy poszczególnych rodzajów układów CHP z tłokowym silnikiem spalinowym, mikroturbiną gazową oraz ogniwem paliwowym.

Tabela 1.4. Porównanie układów CHP w zależności od rodzaju zastosowanego źródła energii napędowej

	Tłokowy silnik spalinowy	Mikroturbina gazowa	Ogniwo paliwowe
Zakres mocy, kW	40-5000	60-350	100-3000
Rodzaj możliwego do zastosowania paliwa	• gaz ziemny, • olej, • gaz wysypiskowy, • biogaz z oczyszczalni ścieków, • biogaz pochodzenia rolniczego, • gaz z odmetanowania kopalń, • gaz odpadowy z procesów technologicznych, • gaz ciekły LPG, • olej napędowy.	W przypadku małych mocy gaz ziemny. W przypadku wyższych mocy (turbiny gazowe) również inne gazy.	• wodór, • propan, • gaz ziemny, • metanol.
Produkcja ciepła	• Ciepło jest pozyskiwane z kilku źródeł: ✓ układ chłodzenia bloku silnika, ✓ układ chłodzenia oleju, ✓ układ chłodzenia sprężanej mieszanki, ✓ układ odprowadzenia spalin, • Konieczność chłodzenia zewnętrznego, • Duży udział ciepła na niskim poziomie temperaturowym.	• Najczęściej jeden wymiennik ciepła spaliny-woda (kocioł odzyskowy) zasilany gorącymi spalinami z turbiny, • Brak konieczności chłodzenia zewnętrznego.	• Najczęściej jeden wymiennik ciepła do produkcji gorącej wody

Sprawność wytwarzania energii elektrycznej w układzie, %	25-42	25-32	40-55
Sprawność całkowita, %	75-90	70-85	80-85
Wskaźnik skojarzenia	0.5-1	0.5-0.65	1-2
Konstrukcja	Znaczne gabaryty oraz duży ciężar.	Małe rozmiary i wysoki stosunek mocy do masy.	Zwarta (kontenerowa) konstrukcja.
Charakter pracy	• Stosunkowo wysoki poziom drgań. • Wysoki poziom hałasu.	Stosunkowo niewielki poziom drgań i hałasu.	Niski poziom hałasu i drgań.
Praca w zależności od warunków zewnętrznych	Mała zależność mocy i sprawności od warunków otoczenia.	Stosunkowo duża zależność mocy i sprawności od temperatury otoczenia.	Mała zależność mocy i sprawności od warunków otoczenia.
Wskaźniki emisji, g/kWh	Silnik gazowy (paliwo: gaz ziemny) NO _x : 0.33-0.84 CO: 0.4-0.81	(paliwo: gaz ziemny) NO _x : 0.29-0.75	NO _x : <0.02 CO: <0.01
Koszty obsługi i remontów, \$/kWh	0.0075-0.02	0.004-0.01	0.002-0.05
Nakład inwestycyjny, \$/kW_{el}	300-1500	350-1500	2000-8000

1.5. Układy trójgeneracyjne w budynkach (BCHP)

Rosnące wymagania związane z zapewnieniem komfortu cieplnego w kompleksach budowlanych prowadzą do zastosowania nowych technologii energetycznych. Coraz częstsze stosowanie urządzeń klimatyzacyjnych w budynkach biurowych i innych budynkach o złożonej strukturze wymaga wytwarzania obok energii elektrycznej i ciepła znacznych ilości chłodu. Tego rodzaju budynki były najczęściej wyposażane w sprężarkowe agregaty chłodnicze przygotowujące wodę lodową na potrzeby klimatyzacji lub produkujące czynnik chłodzący na potrzeby technologiczne. Rozwiązanie takie wiąże się ze znacznym zużyciem energii elektrycznej i wysokimi kosztami eksploatacji budynku. Zwiększenie efektywności produkcji poszczególnych nośników energii w budynku można uzyskać poprzez połączenie skojarzonego układu cieplno-elektrycznego z układami chłodniczymi. Umożliwia to realizację gospodarki elektryczno-cieplno-chłodniczej (trigeneration). Technologię „trigeneration” definiuje się zatem jako skojarzone wytwarzanie ciepła i energii elektrycznej połączone z produkcją chłodu. Systemy pracujące w oparciu o technologię „trigeneration” w kompleksach budowlanych noszą nazwę układów BCHP (ang. Building Cooling, Heating and Power). Jako źródło energii napędowej

w układach BCHP może być wykorzystane ciepło pochodzące z tłokowego silnika spalinowego, turbiny gazowej lub ogniwa paliwowego. Szczególnie poza okresem grzewczym, źródła te dysponują znacznym nadmiarem produkowanego ciepła. Niezagospodarowana moc grzejna może zostać z powodzeniem wykorzystana do wytwarzania chłodu zużywanego na potrzeby klimatyzacji oraz w innych celach technologicznych (np. niskotemperaturowe urządzenia przechowywania spożywczego). Często w przypadku kompleksów budowlanych istnieje potrzeba produkcji czynnika chłodniczego na kilku różnych poziomach temperaturowych. Przykładowo w przypadku hipermarketu często niezbędne są aż trzy czynniki chłodnicze o różnych temperaturach, które zapewniają odbiór ciepła z systemu klimatyzacji, chłodni, ład chłodniczych, wysp mroźniczych, itp. Nadmiarowe ciepło odpadowe z układu skojarzonego może zostać również wykorzystane przez systemy osuszania powietrza w budynkach celem zapewnienia odpowiedniej wilgotności względnej powietrza wewnętrznego. Szczególnie dużym zużyciem energii na potrzeby osuszania powietrza wewnętrznego charakteryzują się hale basenowe.

Jednym z najbardziej efektywnych sposobów utylizacji ciepła w celu wytwarzania chłodu jest zastosowanie absorpcyjnych urządzeń chłodniczych. Chłodziarki absorpcyjne w odróżnieniu od agregatów sprężarkowych nie wymagają znacznych ilości mechanicznej energii napędowej, odznaczają się niewielkimi wymaganiami serwisowymi, dużą trwałością, niezawodnością i umiarkowanym poziomem emitowanego hałasu podczas pracy. Właśnie dlatego chłodziarki absorpcyjne stały się najbardziej popularnymi urządzeniami do produkcji chłodu w systemach BCHP.

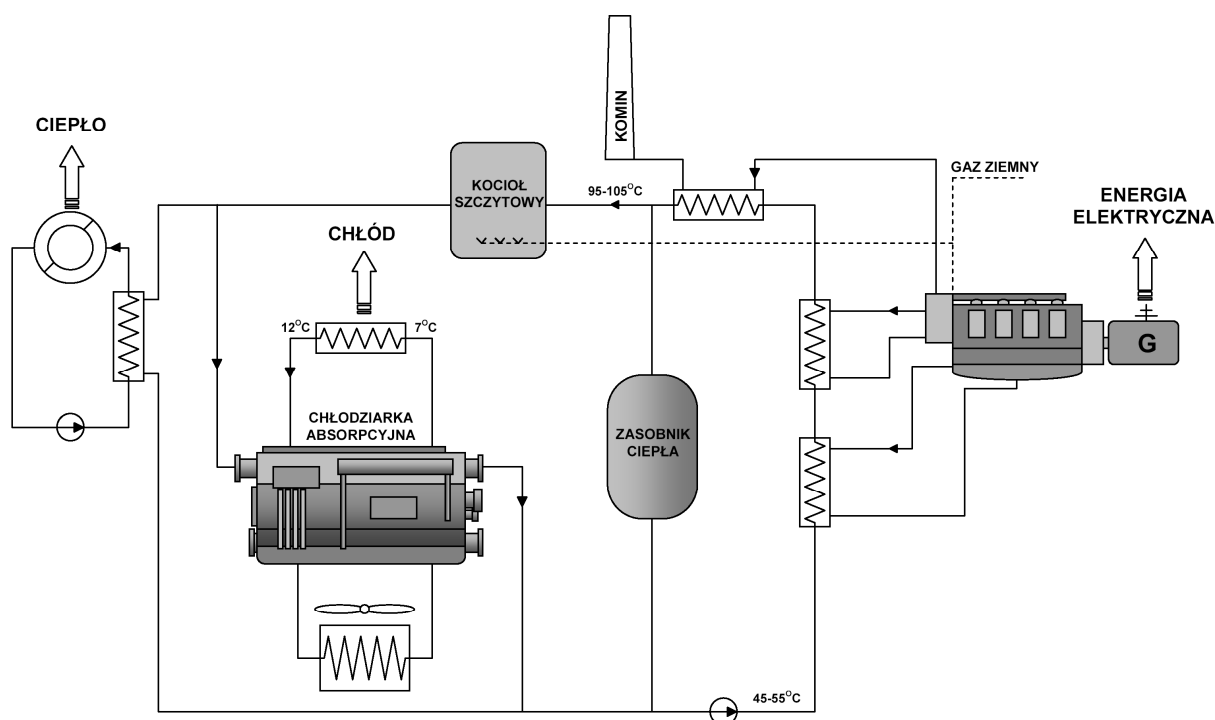
W układach BCHP chłodziarki absorpcyjne są zasilane gorącą wodą, parą lub bezpośrednio spalinami. Obecnie na rynku najbardziej rozpowszechnione są dwa rodzaje chłodziarek absorpcyjnych: chłodziarki bromolitowe oraz amoniakalne. Zwykle w celu zapewnienia zapotrzebowania chłodu na cele klimatyzacji pomieszczeń układy BCHP są wyposażane w chłodziarki bromolitowe, które produkują wodę lodową o parametrach ok. 6/12°C. Absorbentem w tego typu chłodziarkach jest bezpieczny dla otoczenia wodny roztwór bromku litu ($\text{LiBr} + \text{H}_2\text{O}$), a czynnikiem roboczym jest woda. W kompleksach budowlanych, gdzie niezbędna jest niższa temperatura czynnika znajdują zastosowanie absorpcyjne chłodziarki amoniakalne. W urządzeniach tych czynnikiem roboczym jest wodny roztwór amoniaku ($\text{H}_2\text{O} + \text{NH}_3$), co pozwala na obniżenie temperatury czynnika chłodzącego znacznie poniżej 0°C. Urządzenia te w porównaniu z chłodziarkami

bromolitowymi charakteryzują się jednak bardziej skomplikowaną budową oraz wymagają większych nakładów inwestycyjnych. Ze względu na toksyczność amoniaku wymagają również odpowiednich rozwiązań konstrukcyjnych i zabiegów technicznych podnoszących bezpieczeństwo pracy tego typu chłodziarek. Dla obecnie oferowanych chłodziarek absorpcyjnych jednostopniowych wskaźnik efektywności chłodniczej COP sięga wartości około 0.8. W przypadku urządzeń dwustopniowych wskaźnik ten osiąga wartość 1.5. Koncepty efektywnych energetycznie absorpcyjnych chłodziarek trójstopniowych nie osiągnęły jeszcze wystarczająco wysokiego poziomu technologicznego by mogły być stosowane w skali komercyjnej na potrzeby kompleksów budowlanych. Podstawowe parametry kilka wybranych jedno- i dwustopniowych chłodziarek absorpcyjnych zestawiono w tablicy 1.5.

Tablica 1.5. Parametry przykładowych, komercyjnie dostępnych chłodziarek bromolitowych możliwych do zastosowania w układach BCHP

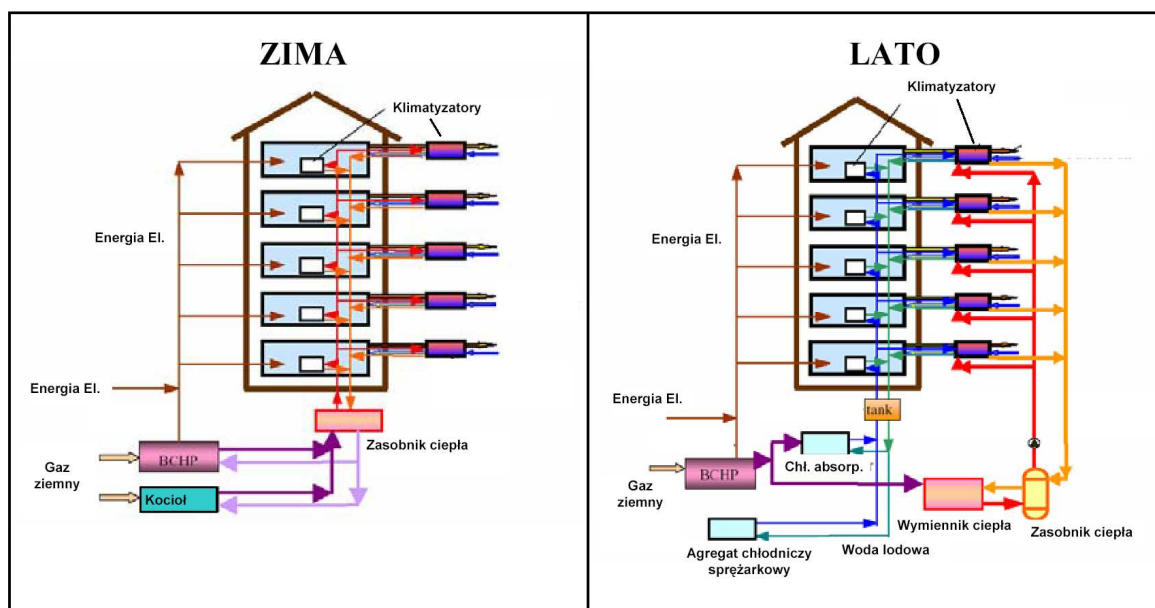
	Układ 1	Układ 2	Układ 3	Układ 4	Układ 5
Rodzaj obiegu	jednostopniowy	jednostopniowy	jednostopniowy	dwustopniowy	dwustopniowy
Źródło ciepła	gorąca woda 90-130°C	gorąca woda 95°C	gorąca woda 90-130°C	gorąca woda 180°C	gorąca woda 180°C
	para wodna		para wodna	para wodna	para wodna
Moc chłodnicza, kW	394	1055	2008	1266	2318
Wskaźnik efektywności chłodniczej COP	0.63	0.7	0.71	1.20	1.21
Zapotrzebowanie mocy elektrycznej, kW	3.8	4.05	9.7	10.6	20.5

Schemat przykładowego układu BCHP do wytwarzania ciepła, chłodu i energii elektrycznej z wykorzystaniem tłokowego silnika spalinowego i chłodziarki absorpcyjnej pokazano na rys. 1.6. Układ ten jest dodatkowo wyposażony w kocioł szczytowy oraz zasobnik ciepła. Gdy zużycie ciepła przez odbiorców jest mniejsze od produkcji w układzie skojarzonym nadmiar ciepła akumuluje się w zasobniku gorącej wody. W okresach zwiększonego zapotrzebowania na ciepło jest ono wytwarzane dodatkowo w gazowym kotle szczytowym połączonym z układem BCHP.



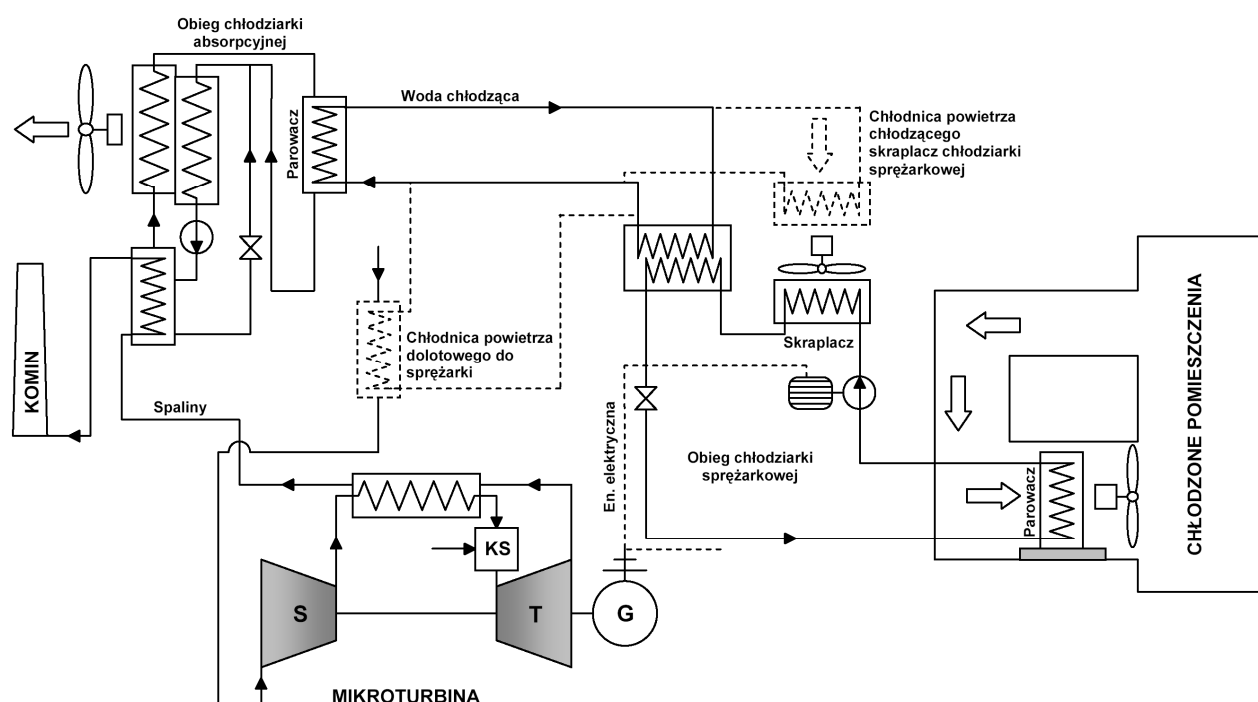
Rys. 1.6. Schemat przykładowego układu BHP

Budynki, w których zainstalowano układ BHP są często dodatkowo wyposażane również w szczytowy, sprężarkowy agregat chłodniczy. Rozwiązanie takie zaprezentowano na rys. 1.7, gdzie przedstawiono schemat zainstalowania układu BHP w budynku biurowym. Układ produkuje elektryczność, ciepło lub chłód w zależności od zapotrzebowania w sezonie. W okresie przejściowym układ nie wytwarza ciepła ani chłodu a zapotrzebowanie na energię elektryczną jest pokrywane z sieci dystrybucyjnej. W przedstawionym na rys. 1.7 rozwiązaniu układ BHP oprócz produkcji podstawowych nośników energii zużywanych w budynku (ciepło, energia elektryczna, chłód) bierze również udział w procesie osuszania powietrza w instalacji klimatyzacji, który jest często niezbędny w celu zapewnienia komfortu cieplnego w budynkach biurowych. Działająca w sezonie letnim instalacja osuszania powietrza pobiera ciepło regeneracji z układu skojarzonego. Chłód niezbędny podczas procesu osuszania jest odzyskiwany z powietrza wylotowego klimatyzowanych pomieszczeń.



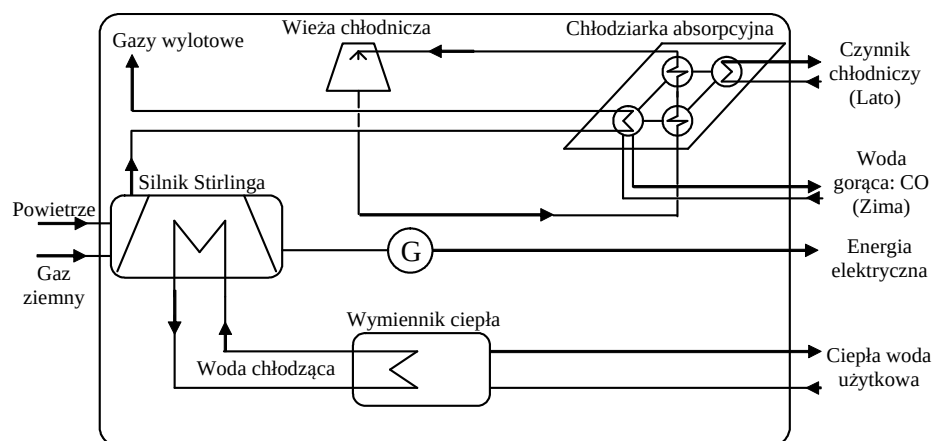
Rys. 1.7. Schemat zainstalowanego układu BCHP w budynku biurowym

W celu zwiększenia efektywności tradycyjnego obiegu chłodniczego z parowym agregatem sprężarkowym można go zintegrować z modułem skojarzonym. Konceptję taką przedstawiono na rys. 1.8. W układzie tym zintegrowano sprężarkową chłodziarkę parową z mikroturbiną gazową i chłodziarką absorpcyjną. Spaliny z mikroturbiny służą jako źródło napędowe chłodziarki absorpcyjnej, która dostarcza dodatkowy chłód. Dodatkowy chłód może zostać wykorzystany w celu zwiększenia efektywności chłodniczej ziębiarki sprężarkowej poprzez ochładzanie czynnika w wymienniku układu chłodzenia przed zaworem dławiącym lub do obniżenia temperatury powietrza chłodzącego skraplacz ziębiarki. Ponadto nadwyżka chłodu może zostać wykorzystana do ochładzania powietrza dolotowego do mikroturbiny, co zwiększa jej sprawność energetyczną. Takie rozwiązania pozwalają na zwiększenie efektywności istniejących układów chłodniczych.



Rys. 1.8. Koncepcja zintegrowanego obiegu parowej chłodziarki sprężarkowej z chłodziarką absorpcyjną i mikroturbiną gazową

Układy kogeneracyjne jak i trójgeneracyjne mogą być również realizowane w oparciu o silnik Stirlinga. Silnik ten pracuje w obiegu zamkniętym i jest połączony z zewnętrznym źródłem ciepła. Z uwagi na proces zewnętrznego spalania tego rodzaju układy mogą być zasilane różnego rodzaju paliwami (również zawierającymi zanieczyszczenia). Charakteryzują się dużą trwałością i niezawodnością (stosunkowo niewielka liczba podzespołów mechanicznych). Praca silnika Stirlinga cechuje się niskim poziomem hałasu oraz niewielkimi wskaźnikami emisji. Niemniej jednak z powodu niskiego poziomu dojrzałości tej technologii silniki Stirlinga nie są wykorzystywane na dużą skalę w kompleksach budowlanych. Na rys. 1.9 przedstawiono układ BCHP bazujący na silniku Stirlinga oraz chłodziarce absorpcyjnej.



Rys. 1.9. Układ BCHP z wykorzystaniem silnika Stirlinga oraz chłodziarki absorpcyjnej

Instalacja systemu BCHP w kompleksie budowlanym jest uzasadniona, gdy przez stosunkowo długi okres w roku występuje zapotrzebowanie na ciepło, chłód oraz energię elektryczną. Wybór rodzaju zastosowanego systemu BCHP oraz jego konfiguracja uzależniona jest od wielkości oraz charakterystyki zapotrzebowania na nośniki energii w kompleksie budowlanym. Wielkość produkcji poszczególnych nośników energii zmienia się w zależności od wymagań procesowych budynku, pory dnia i roku.

2. Algorytm analizy systemowej eksploatacji kompleksu budowlanego użyteczności publicznej

2.1. Model matematyczny bilansu bezpośredniego zużycia energii w gospodarce energetycznej kompleksu budowlanego

Z zebranych na potrzeby bazy wiedzy informacji o nowoczesnych systemach energetycznych w budynkach użyteczności publicznej wynika, że występuje potrzeba opracowania metodyki systemowej analizy gospodarki energetycznej dla tego typu obiektów. Metodyki, która będzie mogła być wykorzystana zarówno do analizy energetyczno-ekologicznej eksploatacji budynków jak również do wspomagania projektowania ich optymalnego wariantu struktury gospodarki energetycznej. Model matematyczny bezpośredniego zużycia energii w gospodarce energetycznej budynku użyteczności publicznej został zbudowany w oparciu o teorię przepływów międzygałęziowych, co umożliwia analizę nie tylko bezpośredniego, ale również pośredniego zużycia nośników energii wynikającego z powiązań międzygałęziowych występujących w rozpatrywanym systemie. Opracowany model bilansu bezpośredniego zużycia energii w kompleksie budowlanym dotyczy bilansowania długoterminowego.

W gospodarce energetycznej kompleksów budowlanych można wyodrębnić dwa charakterystyczne podsystemy: podsystem energetyczny, który jest odpowiedzialny za wytwarzanie, przetwarzanie, przesyłanie i rozdział nośników energii w budynku oraz podsystem odbiorców energii (pomieszczenia, wyposażenie budynku, itp.) umownie nazywany podsystemem technologicznym. Nośniki energii przeznaczone na potrzeby podsystemu technologicznego są wytwarzane w sieci wzajemnie ze sobą powiązanych procesów energetycznych. Szczególną złożonością powiązań charakteryzuje się gospodarka elektryczno-ciepłno-chłodnicza (zastosowanie układów BCHP - *Building Cooling, Heating and Power* w budynkach). Część tych powiązań ma charakter sprzężeń zwrotnych, co utrudnia zamknięcie bilansu energetycznego za pomocą bilansów cząstkowych. Uciążliwej, przybliżonej metody bilansów cząstkowych można uniknąć przez zastosowanie modelu matematycznego bilansu gospodarki energetycznej kompleksu budowlanego.

Założenia modelu matematycznego bilansu gospodarki energetycznej kompleksu budowlanego opierają się na teorii przepływów międzygałęziowych z uzupełnieniami charakterystycznymi dla przemysłowej gospodarki energetycznej. W niektórych gałęziach energetycznych nośniki energii są wytwarzane w urządzeniach szczytowych i podstawowych. W takim przypadku rozróżnia się część szczytową i część podstawową

produkcji nośnika energii. Rozróżnia się także główną i uboczną produkcję nośnika energii. W niektórych przypadkach produkcja nośnika energii jest uzupełniana dostawami zewnętrznymi (np. energia elektryczna w przypadku zainstalowania układu skojarzonego ciepłno-elektrycznego w kompleksie budowlanym).

Przepływy nośników energii w podsystemie energetycznym i technologicznym kompleksów budowlanych można przedstawić w formie tablicy przepływów międzygałęziowych, podobnie jak w przypadku analizy input-output Leontiefa (tablica 2.1). Struktura tej tablicy opiera się na następujących założeniach:

- w podsystemie energetycznym wyróżnia się gałęzie energetyczne; każdej gałęzi odpowiada produkcja jednego nośnika energii,
- nośnik energii może być produktem głównym danej gałęzi energetycznej, produktem ubocznym innych gałęzi, bądź też może być dostarczany z zewnątrz,
- wszystkie nośniki energii są zużywane wewnątrz osłony bilansowej budynku; głównie na potrzeby podsystemu technologicznego ale również w pewnym stopniu przez urządzenia podsystemu energetycznego.

Model matematyczny bilansu gospodarki energetycznej kompleksu budowlanego opiera się na układzie równań bilansowych wykorzystywanym w analizie przepływów międzygałęziowych. Podstawową zasadą modelu matematycznego jest założenie liniowych zależności między produkcją i zużyciem nośników energii w budynku. Przedstawiony model matematyczny został sformułowany w oparciu o prace.

Gałąź energetyczną definiuje się jako grupę urządzeń i instalacji podsystemu energetycznego, która wytwarza określony nośnik energii np.: układ BCHP, system wentylacji, instalacja ogrzewania, system przygotowania ciepłej wody użytkowej. Gałęzie technologiczne w kompleksie budowlanym definiuje się jako odbiorców nośników energii: np. magazyny, biura, hale handlowe, itp.

W tablicy 2.1. przedstawiono strukturę przepływów międzygałęziowych w kompleksie budowlanym. Nośniki energii zostały podzielone na dwie grupy:

- nośniki wytwarzane w podsystemie energetycznym kompleksu budowlanego z możliwością uzupełnienia dostawami z zewnątrz (np. energia elektryczna własna wytwarzana w małym układzie kogeneracyjnym jest zwykle uzupełniana dostawą z krajowego systemu elektroenergetycznego),
- nośniki energii sprowadzane do kompleksu budowlanego z zewnątrz (głównie paliwa).

Tablica 2.1. Tablica przepływów międzygałęziowych

Nośnik energii	Część przychodowa				Część rozchodowa	
	Produkcja główna	Produkcja uboczna		Dostawa zewnętrzna	Przepływy międzygałęziowe	
		Podsystem energetyczny	Podsystem odbiorców		Podsystem energetyczny	Podsystem odbiorców
1	...	...	...	...	...	...
...	...	...	...	...	...	...
i	G_i	$\sum_{j=1}^n U_{i j}$	$\sum_{k=1}^p \bar{U}_{i k}$	D_{Gi}	$\sum_{j=1}^n Z_{ij}^G$	$\sum_{k=1}^p \bar{Z}_{ik}^G$
...	...	...	...	...	...	...
n	...	...	...	...	...	...
$n+1$	...	...	...	...	...	...
...	...	...	...	...	...	...
i	0	0	0	D_{Di}	$\sum_{j=1}^n Z_{ij}^D$	$\sum_{k=1}^p \bar{Z}_{ik}^D$
...	...	...	...	...	...	...
m	...	...	...	...	...	...

Przyjmując założenie o liniowości związków między produkcją i zużyciem nośników energii w kompleksie budowlanym, zużycie i -tego nośnika energii w j -tej gałęzi energetycznej $Z_{i j}$ oraz w k -tej gałęzi technologicznej $\bar{Z}_{i k}$ można ująć w postaci:

$$Z_{i j}^G = a_{i j}^G G_j \quad (2.1)$$

$$\bar{Z}_{i k}^G = \bar{a}_{i k}^G \bar{G}_k \quad (2.2)$$

$$Z_{i j}^D = a_{i j}^D G_j \quad (2.3)$$

$$\bar{Z}_{i k}^D = \bar{a}_{i k}^D \bar{G}_k \quad (2.4)$$

gdzie:

- G_j – produkcja główna j -tej gałęzi energetycznej oraz k -tej gałęzi technologicznej,
- $\bar{G}_k$ – ilość i -tego nośnika energii wytwarzanego i zużywanego w podsystemie energetycznym,
- $Z_{i j}^G$ – ilość i -tego nośnika energii wytwarzanego i zużywanego w podsystemie energetycznym,
- $a_{i j}^G$ – wskaźnik jednostkowego bezpośredniego zużycia i -tego nośnika energii wytwarzanego w podsystemie energetycznym przypadającego na jednostkę ilości produkcji j -tej gałęzi energetycznej,

- $\overline{Z}_{i k}^G$ – zużycie i -tego nośnika energii wytwarzanego w podsystemie energetycznym w k -tej gałęzi technologicznej,
- $\overline{a}_{i j}^G$ – wskaźnik jednostkowego bezpośredniego zużycia i -tego nośnika energii wytwarzanego w podsystemie energetycznym przypadającego na jednostkową wielkość produkcji k -tej gałęzi technologicznej,
- $Z_{i j}^D$ – zużycie i -tego nośnika energii stanowiącego wyłączną dostawę zewnętrzną w j -tej gałęzi energetycznej,
- $a_{i j}^G$ – wskaźnik jednostkowego bezpośredniego zużycia i -tego nośnika energii stanowiącego wyłączną dostawę zewnętrzną w j -tej gałęzi energetycznej,
- $\overline{Z}_{i k}^D$ – zużycie i -tego nośnika energii stanowiącego wyłączną dostawę zewnętrzną w k -tej gałęzi technologicznej.

Podobnie dla ubocznego wytwarzania:

$$U_{i j} = f_{i j} G_j \quad (2.5)$$

$$\overline{U}_{i k} = \overline{f}_{i k} \overline{G}_k \quad (2.6)$$

gdzie:

- $f_{i j}$ – wskaźnik ubocznego wytwarzania i -tego nośnika energii w j -tej gałęzi energetycznej,
- $\overline{f}_{i k}$ – wskaźnik ubocznego wytwarzania i -tego nośnika energii w k -tej gałęzi technologicznej.

W przypadku gdy zużycie nośników energii w gałęzi podsystemu technologicznego stanowi wielkość niezależną od produkcji lub gdy gałąź technologiczna stanowią obiekty (np. pomieszczenia biurowe) wówczas:

$$\overline{Z}_{i k}^G = C_{ik}^G \quad (2.7)$$

$$\overline{Z}_{i k}^D = C_{ik}^D \quad (2.8)$$

gdzie:

- C_{ik}^G – zużycie stałe i -tego nośnika energii wytwarzanego w podsystemie energetycznym w k -tej gałęzi technologicznej,
- C_{ik}^D – zużycie stałe i -tego nośnika energii stanowiącego wyłączną dostawę zewnętrzną w k -tej gałęzi technologicznej.

Układ równań bilansowych nośników energii wytwarzanych w podsystemie energetycznym ma postać:

$$\bigwedge_{i=1}^n G_i + \sum_{j=1}^n f_{i j} G_j + \sum_{k=1}^p \overline{f}_{i k} \overline{G}_k + D_{Gi} = \sum_{j=1}^n a_{ij}^G G_j + \sum_{k=1}^p \overline{a}_{ik}^G \overline{G}_k \quad (2.9)$$

gdzie D_{Gi} oznacza dostawę uzupełniającą i -tego nośnika energii.

Podobnie układ równań bilansowych nośników energii stanowiących dostawy wyłączne można zapisać jako:

$$\bigwedge_{i=1+1}^m D_{Di} = \sum_{j=1}^n a_{ij}^D G_j + \sum_{k=1}^p \bar{a}_{ik}^D \bar{G}_k \quad (2.10)$$

gdzie D_{Di} oznacza dostawę wyłączną i -tego nośnika energii.

W zapisie macierzowym układ równań bilansowych (2.9) ma postać:

$$\mathbf{G} + \mathbf{F}\mathbf{G} + \bar{\mathbf{F}}\bar{\mathbf{G}} + \mathbf{D}_G = \mathbf{A}_G\mathbf{G} + \bar{\mathbf{A}}_G\bar{\mathbf{G}} \quad (2.11)$$

gdzie:

- $\mathbf{A}_G, \bar{\mathbf{A}}_G$ – macierze wskaźników jednostkowego bezpośredniego zużycia nośników energii w podsystemie energetycznym i technologicznym,
- $\mathbf{D}_G$ – wektor dostawy uzupełniającej nośników energii,
- $\mathbf{F}, \bar{\mathbf{F}}$ – macierze współczynników ubocznego wytwarzania nośników energii w podsystemie energetycznym i technologicznym,
- $\mathbf{G}, \bar{\mathbf{G}}$ – wektory produkcji głównej nośników energii w gałęziach energetycznych, bądź w gałęziach technologicznych.

Przekształcając równanie (5.11) otrzymuje się:

$$\mathbf{G} = (\mathbf{E} - \mathbf{A}_G + \mathbf{F})^{-1} [(\bar{\mathbf{A}}_G - \bar{\mathbf{F}})\bar{\mathbf{G}} - \mathbf{D}_G] \quad (2.12)$$

Macierz odwrotna $(\mathbf{E} - \mathbf{A}_G + \mathbf{F})^{-1}$ w równaniu (2.12) zawiera elementy, które uwzględniają nie tylko bezpośrednie ale i pośrednie powiązania między procesami energetycznymi tworzącymi gospodarkę energetyczną kompleksu budowlanego.

Układ równań bilansowych (2.9) dotyczący dostaw zewnętrznych wyłącznych ma w zapisie macierzowym postać:

$$\mathbf{D}_D = \mathbf{A}_D\mathbf{G} + \bar{\mathbf{A}}_D\bar{\mathbf{G}} \quad (2.13)$$

gdzie:

- $\mathbf{D}_D$ – wektor dostaw zewnętrznych wyłącznych do kompleksu budowlanego,
- $\mathbf{A}_D$ – macierz wskaźników jednostkowego bezpośredniego zużycia nośników energii stanowiących dostawę wyłączną w podsystemie energetycznym,
- $\bar{\mathbf{A}}_D$ – macierz wskaźników jednostkowego bezpośredniego zużycia nośników energii stanowiących dostawę wyłączną w podsystemie technologicznym.

Układ równań (2.12) i (2.13) stanowi model matematyczny bilansu bezpośredniego zużycia energii w kompleksie budowlanym.

2.2. Model matematyczny bilansu skumulowanego zużycia energii

Metodologia obliczania wskaźników skumulowanego zużycia energii dla nośników energii w kompleksie budowlanym jest oparta o opisany model matematyczny bilansu gospodarki energetycznej. Dane wejściowe do takiej analizy stanowią wyniki obliczeń bilansu bezpośredniego zużycia energii w kompleksie budowlanym oraz wskaźniki skumulowanego zużycia energii dla nośników energii dostarczanych z zewnątrz (wartości średnich wskaźników skumulowanego zużycia energii w krajowym systemie energetycznym).

W celu określenia relacji opisujących wskaźniki skumulowanego zużycia energii sporządza się bilanse skumulowanego zużycia na wzór liniowego modelu matematycznego gospodarki energetycznej kompleksu budowlanego.

Nośniki energii używane w kompleksie budowlanym mogą być produktami głównymi lub produktami ubocznymi podsystemu energetycznego, bądź mogą być dostarczane z zewnątrz (np. paliwa). Dlatego należy operować pojęciem średnioważonego wskaźnika skumulowanego zużycia energii.

Analiza bezpośredniego zużycia energii nie obejmuje całkowitej energii jaka jest potrzebna do wytworzenia danego użytecznego nośnika energii (produktu). Stosowane bowiem do jego wytworzenia inne nośniki energii (np. paliwa) również wymagają pewnego zużycia energii w pośrednich procesach wytwórczych i transportowych. Tak więc każdy produkt (nośnik energii) jest wytwarzany w wyniku nie tylko bezpośredniego, ale i pośredniego zużycia energii w licznych ogniwach poprzedzających w sieci powiązań energetycznych i technologicznych. Dlatego też kompletna analiza energetyczna powinna być oparta o rachunek skumulowanego zużycia energii. Metodologia obliczania wskaźników skumulowanego zużycia energii dla nośników energii w kompleksie budowlanym jest oparta o opisany wcześniej model matematyczny bilansu gospodarki energetycznej. Dane wejściowe do takiej analizy stanowią wyniki obliczeń bilansu bezpośredniego zużycia energii w kompleksie budowlanym oraz wskaźniki skumulowanego zużycia energii dla nośników energii dostarczanych z zewnątrz (wartości średnich wskaźników skumulowanego zużycia energii w krajowym systemie energetycznym).

Sumę bezpośredniego zużycia energii i zużycia energii w ogniwach pośrednich nazywa się skumulowanym zużyciem energii. Wskaźnik skumulowanego zużycia energii może być obliczany w odniesieniu do konkretnego nośnika energii (np. energii elektrycznej) lub energii pierwotnej (np. gaz ziemny). Można również określić wskaźnik skumulowanego sumarycznego zużycia energii pierwotnej (węgiel kamienny, gaz ziemny, ropa naftowa). W dalszej analizie będą rozpatrywane wskaźniki skumulowanego zużycia energii pierwotnej.

Wskaźnik skumulowanego zużycia energii i -tego nośnika energii przypadający na jednostkę j -tego użytecznego produktu jest zdefiniowany następująco:

$$e_{i j}^* = \frac{\Delta E_i}{\Delta K_j} \quad (2.14)$$

gdzie ΔE_i oznacza przyrost zużycia i -tego nośnika energii (finalnego bądź pierwotnego) wywołany zwiększeniem o ΔK_j wytwarzania j -tego produktu użytecznego.

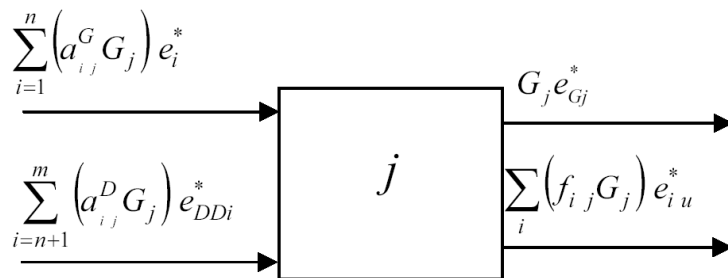
Sumaryczny wskaźnik skumulowanego zużycia energii obejmuje wszystkie postacie energii pierwotnej pochodzące z przyrody:

$$e_j^* = \sum_p e_{p j}^* \quad (2.15)$$

gdzie p oznacza kolejny numer rozpatrywanej postaci energii pierwotnej.

W celu określenia relacji opisujących wskaźniki skumulowanego zużycia energii sporządza się bilanse skumulowanego zużycia na wzór liniowego modelu matematycznego gospodarki energetycznej kompleksu budowlanego.

Nośniki energii zużywane w kompleksie budowlanym mogą być produktami głównymi lub produktami ubocznymi podsystemu energetycznego, bądź mogą być dostarczane z zewnątrz (np. paliwa). Dlatego należy operować pojęciem średnioważonego wskaźnika skumulowanego zużycia energii. Bilans skumulowanego zużycia energii dla j -tej gałęzi energetycznej został przedstawiony na rys. 2.1.



Rys. 2.1. Schemat bilansowy skumulowanego zużycia energii w j -tej gałęzi energetycznej

Na schemacie bilansowym skumulowanego zużycia energii poszczególne symbole oznaczają:

- e_i^* – średnioważony wskaźnik skumulowanego zużycia energii,
- e_{Gj}^* – wskaźnik skumulowanego zużycia energii w gałęzi j dotyczący produktu głównego,
- e_{iu}^* – wskaźnik skumulowanego zużycia energii w odniesieniu do produktów ubocznych,
- e_{DDi}^* – wskaźnik skumulowanego zużycia energii wyłącznej dostawy zewnętrznej.

Elementy wektora $\mathbf{e}^*$ średnioważonych wskaźników skumulowanego zużycia energii są obliczane według relacji:

$$e_i^* = \frac{G_i e_{Gi}^* + e_{iu}^* \left(\sum_{j=1}^n (f_{ij} G_j) + \sum_{k=1}^p (\bar{f}_{ik} \bar{G}_k) \right) + D_{Gi} e_{DGi}^*}{G_i + \sum_{j=1}^n (f_{ij} G_j) + \sum_{k=1}^p (\bar{f}_{ik} \bar{G}_k) + D_{Gi}} \quad (2.16)$$

gdzie e_{DGi}^* oznacza wskaźnik skumulowanego zużycia energii dotyczący uzupełniającej dostawy zewnętrznej.

Tak więc wskaźniki skumulowanego zużycia energii nośników doprowadzanych do gałęzi „ j ” są w ogólnym przypadku wartością średnioważoną ze wskaźników skumulowanego zużycia energii produktu głównego, produktu ubocznego i uzupełniającej dostawy zewnętrznej. Wielkościami wejściowymi (zadanymi) w algorytmie analizy skumulowanego zużycia energii są wskaźniki skumulowanego zużycia energii dostaw zewnętrznych (uzupełniających i wyłącznych) do kompleksu budowlanego (głównie paliwa i energia elektryczna). Wskaźniki skumulowanego zużycia energii dla produktów ubocznych są określane zgodnie z zasadą unikniętych nakładów energetycznych w procesie zastąpionym przez wytwarzanie produktu ubocznego.

Wektor $\mathbf{e}^*$ średnich wskaźników skumulowanego zużycia energii wynika z równania:

$$\mathbf{e}^* = \mathbf{H}^{-1} \left\{ \mathbf{G}^d \mathbf{e}_G^* + [(\mathbf{F}\mathbf{G})^d + (\bar{\mathbf{F}}\bar{\mathbf{G}})^d] \mathbf{e}_u^* + \mathbf{D}_D^d \mathbf{e}_{DG}^* \right\} \quad (2.17)$$

przy czym:

$$\mathbf{H} = \mathbf{G}^d + (\mathbf{F}\mathbf{G})^d + (\bar{\mathbf{F}}\bar{\mathbf{G}})^d + \mathbf{D}_D^d \quad (2.18)$$

gdzie:

- $\mathbf{e}^*$ – wektor średnioważonych wskaźników skumulowanego zużycia energii,
- $\mathbf{e}_G^*$ – wektor wskaźników skumulowanego zużycia energii produktów głównych,
- $\mathbf{FG}$ – wektor produkcji ubocznej w gałęziach energetycznych,
- $\overline{\mathbf{FG}}$ – wektor produkcji ubocznej w gałęziach technologicznych,
- $\mathbf{e}_u^*$ – wektor wskaźników skumulowanego zużycia energii produktów ubocznych,
- $\mathbf{e}_{DG}^*$ – wektor wskaźników skumulowanego zużycia energii uzupełniających dostaw nośników energii z zewnątrz.

Indeks „d” oznacza operację tworzenia macierzy diagonalnej z wektora.

W zapisie macierzowym układ równań bilansu skumulowanego zużycia energii można wyrazić następująco:

$$\mathbf{A}_G^T \mathbf{e}^* + \mathbf{A}_D^T \mathbf{e}_{DD}^* = \mathbf{e}_G^* + \mathbf{F}^T \mathbf{e}_u^* \quad (2.19)$$

przy czym T oznacza operację transponowania macierzy, a indeksy G oraz u dotyczą produkcji głównej i ubocznej nośników energii; macierz $\mathbf{A}_G$ dotyczy zużycia produktów głównych a macierz $\mathbf{A}_D$ zużycia dostaw zewnętrznych wyłącznych, przy czym $\mathbf{e}_{DD}^*$ oznacza wektor wskaźników skumulowanego zużycia energii dotyczący dostaw zewnętrznych wyłącznych.

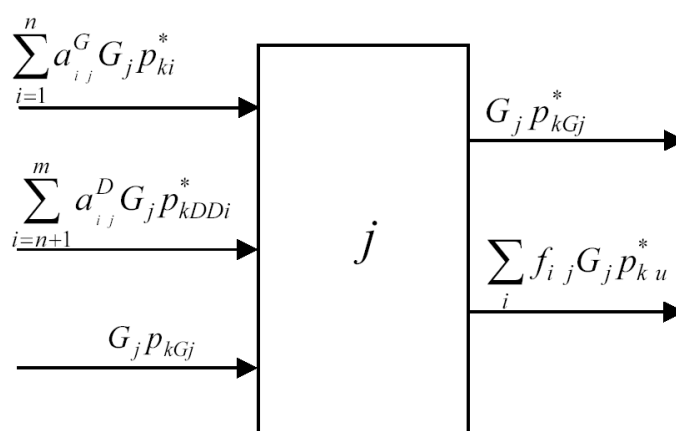
Z równania (2.19), po wykorzystaniu (2.17) i (2.18) oblicza się wektor $\mathbf{e}_G^*$ wskaźników skumulowanego zużycia energii dotyczący nośników energii wytwarzanych jako produkty główne. Ma on postać:

$$\mathbf{e}_G^* = (\mathbf{E} - \mathbf{A}_G^T \mathbf{H}^{-1} \mathbf{G}^d)^{-1} \left[\left\{ \mathbf{A}_G^T \mathbf{H}^{-1} \left[(\mathbf{FG})^d + (\overline{\mathbf{FG}})^d \right] - \mathbf{F}^T \right\} \mathbf{e}_u^* + \mathbf{A}_G^T \mathbf{H}^{-1} \mathbf{D}_G^d \mathbf{e}_{DG}^* + \mathbf{A}_D^T \mathbf{e}_{DD}^* \right] \quad (2.20)$$

Wektory wskaźników skumulowanego zużycia energii $\mathbf{e}_{DG}^*$ i $\mathbf{e}_{DD}^*$ dostaw zewnętrznych są a’priori znane. Wynikają one z analizy skumulowanego zużycia energii gospodarki energetycznej całego kraju. Wektor $\mathbf{e}_u^*$ wskaźników skumulowanego zużycia energii obciążających produkty uboczne, jest jak już wspomniano oceniany na podstawie zasady zastępowania produktów głównych zgodnie z metodą unikniętych nakładów energetycznych.

2.3. Model matematyczny wyznaczania wskaźników skumulowanej emisji szkodliwych substancji

Produkcja nośników energii w kompleksie budowlanym jest nieodłącznie związana z emisją szkodliwych gazów, cieczy i stałych produktów odpadowych. Bezpośrednie zużycie nośników energii (głównie paliw) prowadzi do bezpośredniej emisji związanej z produkcją danego nośnika energii. Ale nośniki te dostarczone do kompleksu budowlanego są już obciążone szkodliwymi emisjami wynikającymi z wcześniejszych etapów produkcji i procesów transportowych. Jest to, podobnie jak w przypadku analizy skumulowanego zużycia energii, rezultatem istnienia energetyczno-technologicznej sieci wzajemnych powiązań. Tak więc obciążenie ekologiczne danego nośnika energii zużywanego w kompleksie budowlanym zależy nie tylko od bezpośredniej emisji, ale także od emisji, która miała miejsce w procesach poprzedzających i w transporcie. Tak więc analogicznie jak w przypadku wskaźników skumulowanego zużycia energii należy posłużyć się wskaźnikami skumulowanej emisji. Na rys. 2.2 przedstawiono schemat bilansowy skumulowanych emisji szkodliwych substancji dla j -tej gałęzi.



Rys. 2.2. Schemat bilansowy skumulowanej emisji

Na rys. 2.2 poszczególne symbole oznaczają:

- p_{ki}^* – skumulowaną emisję k -tego rodzaju dotyczącą i -tego nośnika energii,
- p_{kDDi}^* – skumulowaną emisję k -tego rodzaju dotyczącą i -tej dostawy zewnętrznej wyłączonej,
- p_{kGj} – emisję bezpośrednią k -tego rodzaju powstającą w procesach należących do j -tej gałęzi,
- p_{kui}^* – emisję skumulowaną k -tego rodzaju obciążającą i -ty produkt uboczny wyznaczaną w oparciu o efekt zastępowania produktu głównego przez produkt uboczny.

Średnioważony skumulowany wskaźnik emisji k -tego rodzaju obciążający i -ty produkt główny jest obliczany z relacji:

$$p_{ki}^* = \frac{G_i p_{kGi}^* + \left(\sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k \right) p_{kui}^* + D_{Gi} p_{kDGi}^*}{G_i + \sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k + D_{Gi}} \quad (2.21)$$

gdzie p_{kDGi}^* oznacza wskaźnik skumulowanej emisji k -tego rodzaju dostawy uzupełniającej.

W zapisie macierzowym otrzymuje się:

$$\mathbf{p}_k^* = \mathbf{H}^{-1} \left\{ \mathbf{G}^d \mathbf{p}_{kG}^* + \left[(\mathbf{F}\mathbf{G})^d + (\bar{\mathbf{F}}\bar{\mathbf{G}})^d \right] \mathbf{p}_{ku}^* + \mathbf{D}_G^d \mathbf{p}_{kDG}^* \right\} \quad (2.22)$$

gdzie:

- $\mathbf{p}_k^*$ – wektor średnioważonych wskaźników skumulowanych emisji k -tego rodzaju,
- $\mathbf{p}_{kG}^*$ – wektor wskaźników skumulowanych emisji k -tego rodzaju obciążający produkcję główną,
- $\mathbf{p}_{ku}^*$ – wektor wskaźników skumulowanych emisji k -tego rodzaju obciążający produkcję uboczną,
- $\mathbf{p}_{kDG}^*$ – wektor skumulowanych emisji k -tego rodzaju obciążający dostawy uzupełniające nośników energii z zewnątrz.

Wektor $\mathbf{H}$ jest obliczany według równania (2.18). Na podstawie schematu bilansowego skumulowanej emisji układ równań w zapisie macierzowym służący do obliczania wskaźników skumulowanych emisji ma postać:

$$\mathbf{A}_G^T \mathbf{p}_k^* + \mathbf{A}_D^T \mathbf{p}_{kDD}^* + \mathbf{p}_{kG} = \mathbf{p}_{kG}^* + \mathbf{F}^T \mathbf{p}_{ku}^* \quad (2.23)$$

gdzie:

- $\mathbf{p}_{kDD}^*$ – wektor wskaźników skumulowanych emisji k -tego rodzaju dostaw wyłącznych nośników energii,
- $\mathbf{p}_{kG}$ – wektor wskaźników bezpośredniej emisji k -tego rodzaju obciążający produkcję główną nośników energii.

Z równań (2.23) i (2.22) wyznacza się wektor $\mathbf{p}_{kG}^*$.

$$\mathbf{p}_{kG}^* = \left(\mathbf{E} - \mathbf{A}_G^T \mathbf{H}^{-1} \mathbf{G}^d \right)^{-1} \left[\mathbf{p}_{kG} + \mathbf{A}_D^T \mathbf{p}_{kDD}^* + \mathbf{A}_G^T \mathbf{H}^{-1} \mathbf{D}_G^d \mathbf{p}_{kDD}^* + \right. \\ \left. + \left\{ \mathbf{A}_G^T \mathbf{H}^{-1} \left[(\mathbf{F}\mathbf{G})^d + (\overline{\mathbf{F}\mathbf{G}})^d \right] - \mathbf{F}^T \right\} \mathbf{p}_{ku}^* \right] \quad (2.24)$$

Wektory $\mathbf{p}_{kDD}^*$ i $\mathbf{p}_{kDG}^*$ wskaźników skumulowanych emisji obciążających dostawy zewnętrzne nośników energii są a priori znane i wynikają z analizy dotyczącej sieci wzajemnych powiązań w skali kraju. Wektor $\mathbf{p}_{ku}^*$ dotyczący produktów ubocznych jest wyznaczany w oparciu o metodę zastępowania, która bazuje na zasadzie unikniętych emisji.

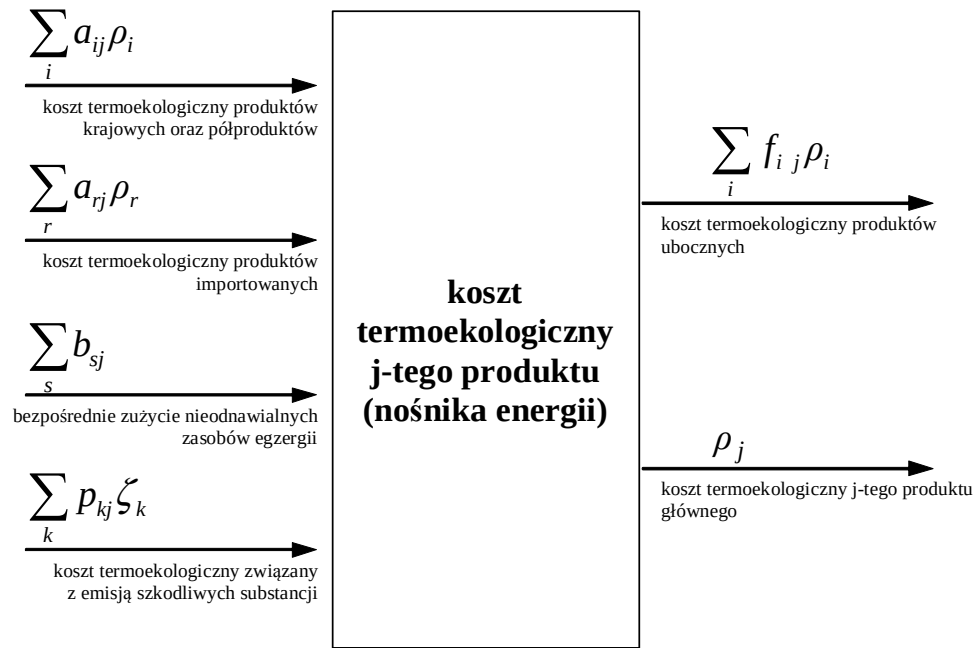
2.4. Model matematyczny wyznaczania wskaźników kosztu termoeekologicznego

Eksplatacja kompleksu budowlanego jest możliwa dzięki zużyciu nieodnawialnych zasobów energetycznych. Dążenie do minimalizacji zużycia nieodnawialnych zasobów energii staje się coraz częściej kluczową sprawą z uwagi na zrównoważony rozwój ludzkości. Jakość nieodnawialnych zasobów energii powinna być określona za pomocą egzergii, ponieważ skład i koncentracja bogactw naturalnych różnią się od powszechnie występującej w otoczeniu. Skumulowane zużycie nieodnawialnych zasobów egzergii związane z wytworzeniem określonego produktu może zostać użyte jako miara zubożenia nieodnawialnych zasobów w związku z działaniem kompleksu budowlanego. Miara ta została określona jako *koszt termoeekologiczny* danego nośnika energii bądź produktu. Koszt termoeekologiczny można zatem zdefiniować jako skumulowane zużycie nieodnawialnych zasobów egzergii połączone z wytwarzaniem danego nośnika energii bądź produktu oraz z koniecznością kompensacji strat w środowisku naturalnym wywołanych przez emisję szkodliwych substancji. Wskaźniki kosztu termoeekologicznego mogą zostać wyznaczone w oparciu o równania bilansu kosztu termoeekologicznego kompleksu budowlanego.

Koncepcję bilansu kosztu termoeekologicznego wyrażoną równaniem (2.25) pokazano na rys. 2.3. Równanie bilansu kosztu termoeekologicznego dla j -tej gałęzi energetycznej zawiera:

- koszt termoeekologiczny krajowych nośników energii i półproduktów,
- koszt termoeekologiczny wyrobów importowanych,
- bezpośrednie zużycie egzergii nieodnawialnych zasobów energetycznych,

- koszt termoeekologiczny produktów ubocznych zastępujących inne użyteczne nośniki energii (np. czynnik chłodzący z układu trigeneration zastępuje chłód wytwarzany w sprężarkowym agregacie chłodniczym) w rezultacie zmniejszając koszt termoeekologiczny obciążający produkt główny.



Rys. 2.3. Schemat bilansowy obliczania kosztu termoeekologicznego

Równanie bilansowe kosztu termoeekologicznego dla j -tej gałęzi energetycznej w kompleksie budowlanym przyjmuje formę:

$$\rho_j + \sum_i f'_{ij} \rho_{iu} = \sum_i a_{ij} \rho_i + \sum_r a_{rj} \rho_r + \sum_s b_{sj} + \sum_k p_{kj} \zeta_k \quad (2.25)$$

gdzie:

- ρ_j, ρ_i – wskaźnik kosztu termoeekologicznego j -tego lub i -tego produktu głównego,
- ρ_{iu} – wskaźnik kosztu termoeekologicznego produktu ubocznego,
- a_{rj} – wskaźnik jednostkowego zużycia produktu importowanego,
- ρ_r – koszt termoeekologiczny jednostki r -tego surowca lub półwyrobu importowanego,
- b_{sj} – egzergia s -tego nieodnawialnego bogactwa naturalnego zużywanego bezpośrednio w j -tym procesie na jednostkę produktu głównego,
- p_{kj} – ilość k -tego agresywnego składnika produktów odpadowych odprowadzanych do otoczenia na jednostkę j -tego produktu głównego,
- ζ_K – skumulowane zużycie energii nieodnawialnych bogactw naturalnych przypadające na jednostkę produktu szkodliwego,
- a_{ij}, f'_{ij} – wskaźniki jednostkowego zużycia i ubocznego wytwarzania.

Wskaźnik kosztu termoeekologicznego produktu ubocznego wyznacza się w oparciu o zasadę zastępowania produktu głównego przez produkt uboczny, co prowadzi do relacji:

$$\rho_{iu} = Z_{iu} \rho_i \quad (2.26)$$

gdzie Z_{iu} oznacza stosunek (sprawność) zastępowania i -tego produktu głównego przez produkt uboczny.

Można wówczas równanie (2.25) bilansu kosztu termoeekologicznego zapisać w postaci:

$$\rho_j + \sum_i (f_{ij} - a_{ij}) \rho_i - \sum_r a_{rj} \rho_r = \sum_s b_{sj} + \sum_K p_{kj} \zeta_k \quad (2.27)$$

przy czym

$$f_{ij} = Z_{iu} f'_{ij} \quad (2.28)$$

Koszt termoeekologiczny produktów importowanych jest oceniany za pomocą odpowiadającego mu kosztu termoeekologicznego wyrobów eksportowanych. Przy założeniu, że koszt termoeekologiczny surowców i półwyrobów importowanych jest w odniesieniu do jednostki dewizowej taki sam jak dla wyrobów eksportowanych można napisać:

$$\rho_r = \frac{\sum_i S_i \rho_i}{\sum_i S_i D_i} D_r \quad (2.29)$$

gdzie:

- S_i – wielkość eksportu i -tego produktu,
- ρ_i – wskaźnik kosztu termoeekologicznego i -tego produktu eksportowanego,
- D_i – wartość dewizowa i -tego produktu eksportowanego,
- D_r – wartość dewizowa r -tego produktu importowanego.

W pracy zachowano konwencję schematu bilansowego obliczania kosztu termoeekologicznego i zapis równań (2.25) i (2.27) zgodnie z literaturą. W nawiązaniu do tablicy przepływów międzygałęziowych (tablica 2.1) należy pamiętać, że wskaźnik a_{ij} należy utożsamiać ze wskaźnikami a_{ij}^G , zaś wskaźniki a_{rj} i b_{sj} ze wskaźnikami a_{ij}^D .

3. Przykład obliczeniowy zastosowania analizy systemowej eksploatacji gospodarki energetycznej kompleksu budowlanego

3.1. Opis analizowanego kompleksu budowlanego

Wykorzystując model matematyczny bilansu bezpośredniego zużycia energii (rozdział 2) przeprowadzono analizę systemową eksploatacji przykładowego budynku. Analizowanym kompleksem budowlanym był typowy biurowiec, który został ukończony w 1999 roku. Powierzchnia użytkowa budynku wynosi 8000m^2 . W budynku znajdują się również przestrzenie parkingowe, które nie są ogrzewane i klimatyzowane, są jedynie wentylowane za pomocą systemu mechanicznej wentylacji wyciągowej. W budynku tym można wyróżnić dwa rodzaje pomieszczeń: pomieszczenia biurowe wyposażone w klimatyzatory oraz pomieszczenia ogólnego przeznaczenia z centralnym systemem ogrzewania. Do klimatyzatorów w pomieszczeniach biurowych w zależności od zapotrzebowania dostarczane jest ciepło oraz chłód z jednostek centralnych (wymiennikownia ciepła, agregat chłodniczy). Wymiennikownia ciepła dostarcza gorącą wodę ($60/45^{\circ}\text{C}$) zimą, a sprężarkowy agregat chłodniczy dostarcza czynnik chłodzący (woda-glikol $6/12^{\circ}\text{C}$) zimą. System wentylacji działa tylko w godzinach pracy biur. Usytuowana na siódmym piętrze centrala klimatyzacyjna dostarcza odpowiednią ilość powietrza do wszystkich pomieszczeń przy natężeniu przepływu $22500\text{ m}^3/\text{h}$. Centrala posiada dwa wentylatory (wyciągowy i zasysający) o mocach 15 kW i 11 kW, wymienniki ciepła, filtry, tłumik hałasu, rekuperator oraz układ sterowania. Centrala klimatyzacyjna zapewnia wymagane parametry powietrza nawiewanego. Temperatura wewnątrz pomieszczeń jest utrzymywana za pomocą klimatyzatorów w pomieszczeniach biurowych oraz systemu centralnego ogrzewania w pomieszczeniach ogólnego przeznaczenia. Ciepło dostarczane jest do stacji wymienników ciepła w budynku za pomocą sieci ciepłowniczej. Wymiennikownia składa się z trzech wymienników ciepła: na potrzeby ciepłej wody użytkowej (o mocy 39 kW), na potrzeby gorącej wody procesowej (293 kW) oraz dla systemu centralnego ogrzewania (100 kW). Instalacja gorącej wody procesowej dostarcza ciepło do centrali klimatyzacyjnej oraz do klimatyzatorów w pomieszczeniach biurowych. Do pomieszczeń ogólnego przeznaczenia ciepło jest dostarczane przez system centralnego ogrzewania. Eksploatacja budynku wymaga dostarczania następujących nośników energii: ciepła (dostawa z sieci ciepłowniczej), elektryczności (z sieci elektroenergetycznej), gazu ziemnego oraz wody wodociągowej. Na rysunku 3.1 przedstawiono schemat powiązań międzygałęziowych

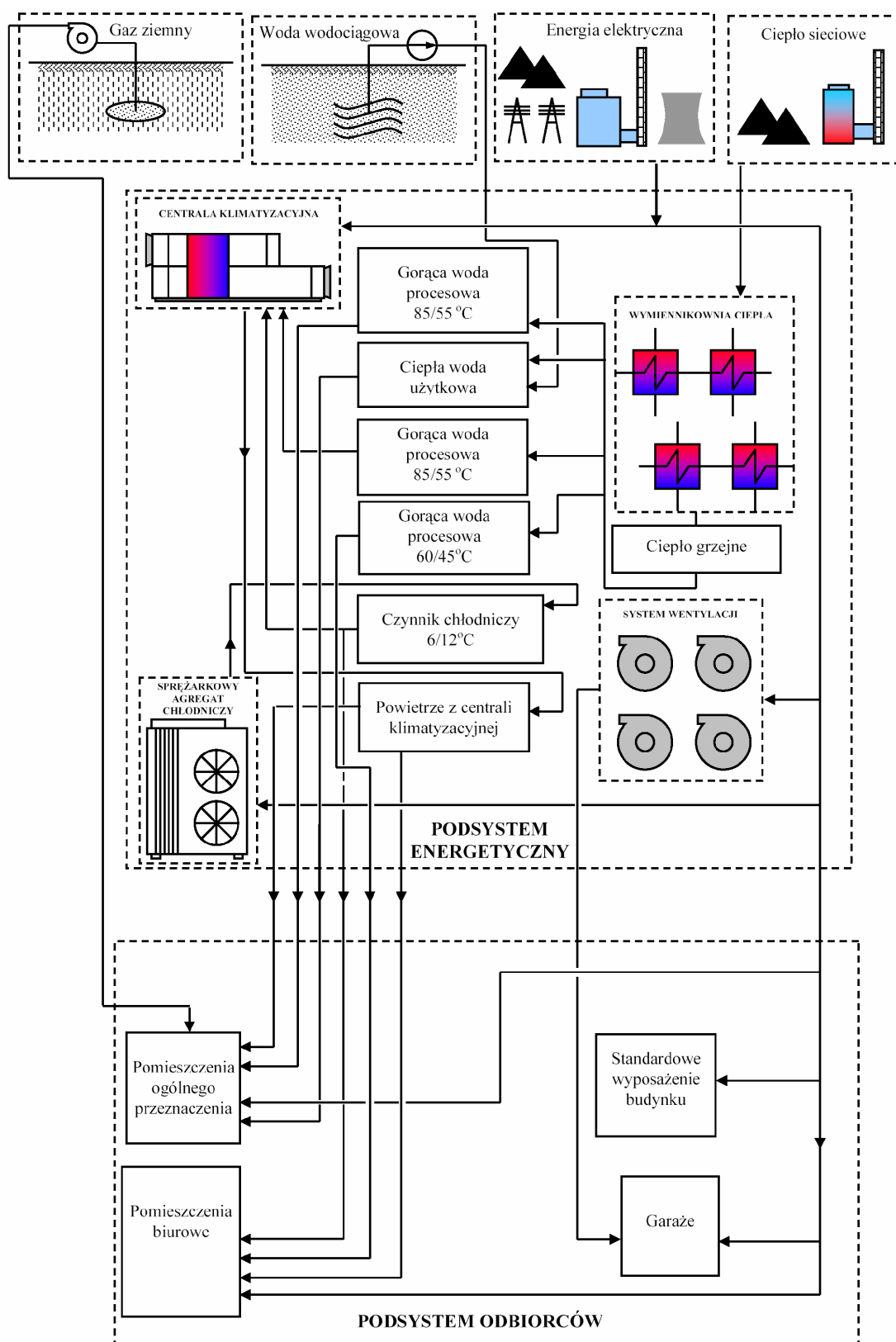
pomiędzy nośnikami energii dostarczanyymi do rozpatrywanego budynku, a nośnikami, które są w nim wytwarzane.

W podsystemie energetycznym budynku wytwarzane są następujące nośniki energii:

- czynnik chłodzący (woda-glikol) 6/12°C,
- gorąca woda procesowa (na cele centralnego ogrzewania oraz centrali klimatyzacyjnej) 85/55 °C,
- ciepła woda użytkowa,
- ciepła woda procesowa 60/45 °C (na cele klimatyzatorów),
- powietrze klimatyzacyjne.

Podsystem odbiorców nośników energii obejmuje:

- pomieszczenia biurowe wyposażone w klimatyzatory,
- pomieszczenia ogólnego przeznaczenia z centralnym systemem ogrzewania,
- standardowe wyposażenie budynku, takie jak: monitoring, systemy bezpieczeństwa, oświetlenie zewnętrzne, itp.
- przestrzeń parkingową z mechaniczną wentylacją wyciągową.



Rys. 3.1. Schemat powiązań międzygałęziowych nośników energii dla przykładowego budynku

3.2. Analiza systemowa bezpośredniego zużycia energii

Liniowy model matematyczny bilansu gospodarki energetycznej rozpatrywanego kompleksu budowlanego został sformułowany na podstawie ogólnej metodologii opisanej w rozdziale 5. Tablica 3.1 przedstawia przepływy międzygałęziowe („input-output analysis”), dla analizowanego kompleksu budowlanego. W rozpatrywanym przypadku zużycia nośników energii w podsystemie odbiorców są narzucone jako stałe wielkości zapotrzebowania energii dla poszczególnych rodzajów pomieszczeń.

Tablica 3.1. Tablica „input-output” analizowanego budynku

	Nośnik energii	Jed.	Produkcja G	Dostawa D	Przepływy międzygałęziowe									
					Podsystem energetyczny						Podsystem odbiorców			
					1	2	3	4	5	6	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaze	Standardowe wyposażenie budynku
											1	2	3	4
1	Czynnik chłodzący (woda- glikol) 6/12°C	GJ	G ₁						Z ₁₅ ^G		Z ₁₁ ^G			
2	Ciepła woda procesowa 85/55°C	GJ	G ₂						Z ₂₅ ^G			Z ₂₂ ^G		
3	Ciepła woda użytkowa	t	G ₃									Z ₃₂ ^G		
4	Ciepła woda procesowa 60/45°C	GJ	G ₄								Z ₄₁ ^G			
5	Powietrze z centrali klimatyzacyjnej	t	G ₅								Z ₅₁ ^G	Z ₅₂ ^G		
6	Powietrze wyciągowe z garaży	t	G ₆										Z ₆₃ ^G	
7	Energia elektryczna	GJ		D ₇	Z ₇₁ ^D	Z ₇₂ ^D	Z ₇₃ ^D	Z ₇₄ ^D	Z ₇₅ ^D	Z ₇₆ ^D	Z ₇₁ ^G	Z ₇₂ ^G	Z ₇₃ ^G	Z ₇₄ ^G
8	Woda wodociągowa	t		D ₈			Z ₈₃ ^D					Z ₈₂ ^G		
9	Gaz sieciowy	GJ		D ₉								Z ₉₂ ^G		
10	Ciepło z sieci ciepłowniczej	GJ		D ₁₀		Z ₁₀₂ ^D	Z ₁₀₃ ^D	Z ₁₀₄ ^D						

Po uproszczeniach główne równania bilansowe w przypadku analizowanego kompleksu budowlanego mają postać:

$$\mathbf{G} = \mathbf{A}_G \mathbf{G} + \overline{\mathbf{A}}_G \overline{\mathbf{G}} \quad (3.1)$$

$$\mathbf{D}_D = \mathbf{A}_D \mathbf{G} + \overline{\mathbf{A}}_D \overline{\mathbf{G}} \quad (3.2)$$

przy czym:

$$\overline{\mathbf{A}}_G \overline{\mathbf{G}} = \mathbf{C}_1^G + \mathbf{C}_2^G + \mathbf{C}_3^G \quad (3.3)$$

$$\overline{\mathbf{A}}_D \overline{\mathbf{G}} = \mathbf{C}_1^D + \mathbf{C}_2^D + \mathbf{C}_3^D + \mathbf{C}_4^D \quad (3.4)$$

gdzie:

$\mathbf{C}_1 = \mathbf{C}_1^G + \mathbf{C}_1^D$ – macierz kolumnowa dotycząca zużycia nośników energii przez pomieszczenia biurowe,

$\mathbf{C}_2 = \mathbf{C}_2^G + \mathbf{C}_2^D$ – macierz kolumnowa dotycząca zużycia nośników energii przez pomieszczenia ogólnego przeznaczenia,

$C_3 = C_3^G + C_3^D$ – macierz kolumnowa dotycząca zużycia nośników energii przez garaże,

$C_4 = C_4^D$ – macierz kolumnowa dotycząca zużycia nośników energii przez system standardowego wyposażenia budynku.

Układ równań bilansu energetycznego w rozpatrywanym budynku:

$$\begin{aligned}
 G_1 &= a_{15}^G G_5 + \bar{Z}_{11}^G \\
 G_2 &= a_{25}^G G_5 + \bar{Z}_{22}^G \\
 G_3 &= \bar{Z}_{32}^G \\
 G_4 &= \bar{Z}_{41}^G \\
 G_5 &= \bar{Z}_{51}^G + \bar{Z}_{52}^G \\
 G_6 &= \bar{Z}_{63}^G \\
 D_7 &= a_{71}^D G_1 + a_{72}^D G_2 + a_{73}^D G_3 + a_{74}^D G_4 + a_{75}^D G_5 + a_{76}^D G_6 + \bar{Z}_{71}^D + \bar{Z}_{72}^D + \bar{Z}_{73}^D + \bar{Z}_{74}^D \\
 D_8 &= a_{83}^D G_3 + \bar{Z}_{82}^D \\
 D_9 &= \bar{Z}_{92}^D \\
 D_{10} &= a_{102}^D G_2 + a_{103}^D G_3 + a_{104}^D G_4
 \end{aligned} \tag{3.5}$$

Na podstawie danych projektowych obliczono roczne wielkości zużyć nośników energii w rozpatrywanym budynku.

Niezerowe elementy wektora C_1 wynoszą:

$$\begin{aligned}
 \bar{Z}_{11}^G &= 1058.58 \text{ GJ} = 294.05 \text{ MWh} && \text{- roczne zużycie chłodu przez klimatyzatory wewnątrz pomieszczeń biurowych,} \\
 \bar{Z}_{41}^G &= 1677.11 \text{ GJ} = 465.86 \text{ MWh} && \text{- roczne zużycie ciepła w pomieszczeniach biurowych,} \\
 \bar{Z}_{51}^G &= 45544.8 \text{ t} && \text{- roczne zużycie powietrza z centrali klimatyzacyjnej w pomieszczeniach biurowych,} \\
 \bar{Z}_{71}^D &= 2639.22 \text{ GJ} = 733.12 \text{ MWh} && \text{- roczne zużycie energii elektrycznej w pomieszczeniach biurowych.}
 \end{aligned}$$

Niezerowe elementy wektora C_2 :

- $\overline{Z}_{22}^G = 851.8 \text{ GJ} = 236.61 \text{ MWh}$ - roczne zużycie ciepła w pomieszczeniach ogólnego przeznaczenia,
 $\overline{Z}_{32}^G = 994.6 \text{ t}$ - roczne zużycie ciepłej wody użytkowej,
 $\overline{Z}_{52}^G = 30363.2 \text{ t}$ - roczne zużycie powietrza klimatyzacyjnego w pomieszczeniach ogólnego przeznaczenia,
 $\overline{Z}_{72}^D = 79.22 \text{ GJ} = 22.0 \text{ MWh}$ - roczne zużycie elektryczności w pomieszczeniach ogólnego przeznaczenia,
 $\overline{Z}_{82}^D = 10085 \text{ t}$ - roczne zużycie wody wodociągowej,
 $\overline{Z}_{92}^D = 576 \text{ GJ} = 160 \text{ MWh}$ - roczne zużycie gazu ziemnego na potrzeby przygotowania posiłków.

Niezerowe elementy wektora C_3 :

- $\overline{Z}_{63}^G = 435591 \text{ t}$ - roczna ilość powietrza wentylacyjnego z garaży,
 $\overline{Z}_{73}^D = 397.33 \text{ GJ} = 110.37 \text{ MWh}$ - roczne zużycie elektryczności przez garaże.

Niezerowy element wektora C_4 :

- $\overline{Z}_{74} = 246.7 \text{ GJ} = 68.53 \text{ MWh}$ - roczne zużycie energii elektrycznej przez system standardowego wyposażenia budynku.

Niezerowe elementy zużycia energii w gałęziach energetycznych:

- $Z_{15}^G = 69.78 \text{ GJ} = 19.38 \text{ MWh}$ - roczne zużycie chłodu w centrali klimatyzacyjnej,
 $Z_{25}^G = 975.9 \text{ GJ} = 271.08 \text{ MWh}$ - roczne zużycie ciepła w centrali klimatyzacyjnej (zapotrzebowanie na wentylację),
 $Z_{71}^D = 548.2 \text{ GJ} = 152.28 \text{ MWh}$ - roczne zużycie energii elektrycznej na produkcję chłodu,
 $Z_{72}^D = 44.1 \text{ GJ} = 12.25 \text{ MWh}$ - roczne zużycie elektryczności do produkcji gorącej wody procesowej 85/55 °C,
 $Z_{73}^D = 3.62 \text{ GJ} = 1.01 \text{ MWh}$ - roczne zużycie energii elektrycznej do produkcji ciepłej wody użytkowej,

$Z_{7\ 4}^D = 7.88\ GJ = 2.19\ MWh$	- roczne zużycie energii elektrycznej w instalacji przygotowania ciepłej wody procesowej dla klimatyzatorów 60/45°C,
$Z_{7\ 5}^D = 269.9\ GJ = 74.97\ MWh$	- roczne zużycie elektryczności na potrzeby wentylacji pomieszczeń biurowych oraz pomieszczeń ogólnego przeznaczenia,
$Z_{7\ 6}^D = 387.89\ GJ = 107.75\ MWh$	- roczne zużycie elektryczności przez system mechanicznej wentylacji garaży,
$Z_{8\ 3}^D = 994.6\ t$	- roczne zużycie wody pitnej na potrzeby ciepłej wody użytkowej,
$Z_{10\ 2}^D = 1827.66\ GJ = 507.68\ MWh$	- roczne zużycie ciepła na potrzeby gorącej wody procesowej 85/55°C,
$Z_{10\ 3}^D = 170.53\ GJ = 47.37\ MWh$	- roczne zużycie ciepła na potrzeby ciepłej wody użytkowej,
$Z_{10\ 4}^D = 1677.11\ GJ = 465.86\ MWh$	- roczne zużycie ciepła na potrzeby ciepłej wody procesowej 60/45°C.

Tablica 3.2. Macierze wskaźników a_{ij}^G i a_{ij}^D zużycia nośników energii w gałęziach energetycznych

	Nośniki energii	1	2	3	4	5	6
1	Czynnik chłodzący (woda-glikol) 6/12°C	0	0	0	0	0,000919	0
2	Ciepła woda procesowa 85/55 °C	0	0	0	0	0,01286	
3	Ciepła woda użytkowa	0	0	0	0	0	0
4	Ciepła woda procesowa 60/45 °C	0	0	0	0	0	0
5	Powietrze z centrali klimatyzacyjnej	0	0	0	0	0	0
6	Powietrze wyciągowe z garaży	0	0	0	0	0	0
7	Energia elektryczna	0,4576	0,02413	0,00364	0,004699	0,003556	0,000890
8	Woda wodociągowa	0	0	1	0	0	0
9	Gaz sieciowy	0	0	0	0	0	0
10	Ciepło z sieci ciepłowniczej	0	1	0,1715	1	0	0

Tablica 3.2 przedstawia macierze A_G i A_D wskaźników jednostkowego zużycia nośników energii w podsystemie energetycznym budynku. Wymiary współczynników

macierzy A_G i A_D wynikają z przyjętych jednostek dla nośników energii. Przykładowo wskaźnik a_{25} dotyczący zużycia gorącej wody procesowej 85/55°C do produkcji powietrza w centrali klimatyzacyjnej jest wyrażony w GJ/t. Tablica 3.3 przedstawia wartości zużycia nośników energii w podsystemie odbiorców. Tablica 3.4 ujmuje rezultaty bilansu energetycznego analizowanego budynku.

Tablica 3.3. Wektory kolumnowe C1, C2, C3, C4, wartości rocznych zużyć nośników energii w podsystemie odbiorców

	Nośniki energii	Jed.	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodzący (woda- glikol) 6/12°C	GJ	1059	0	0	0
2	Ciepła woda procesowa 85/55 °C	GJ	0	851,8	0	0
3	Ciepła woda użytkowa	t	0	994,6	0	0
4	Ciepła woda procesowa 60/45 °C	GJ	1677,11	0	0	0
5	Powietrze z centrali klimatyzacyjnej	t	455448	30363,2	0	0
6	Powietrze wyciągowe z garaży	t	0	0	435591	0
7	Energia elektryczna	GJ	2639,22	79,22	397,33	246,7
8	Woda wodociągowa	t	0	10085	0	0
9	Gaz sieciowy	GJ	0	576	0	0
10	Ciepło z sieci ciepłowniczej	GJ	0	0	0	0

Tablica 3.4. Wektor produkcji rocznej G oraz dostawy zewnętrznej D_D nośników energii

	Nośniki energii	Jed.	Produkcja G	Dostawa D
1	Czynnik chłodzący (woda- glikol) 6/12°C	GJ	1128	0
2	Ciepła woda procesowa 85/55 °C	GJ	1828	0
3	Ciepła woda użytkowa	t	994,6	0
4	Ciepła woda procesowa 60/45 °C	GJ	1677	0
5	Powietrze z centrali klimatyzacyjnej	t	75908	0
6	Powietrze wyciągowe z garaży	t	435591	0
7	Energia elektryczna	GJ	0	4608
8	Woda wodociągowa	t	0	11080
9	Gaz sieciowy	GJ	0	576
10	Ciepło z sieci ciepłowniczej	GJ	0	3675

3.3. Analiza skumulowanego zużycia energii

Bilans skumulowanego zużycia energii został wykonany dla opisanego w punkcie 3.1. przykładowego kompleksu budowlanego. W analizie bazowano na wynikach bilansu bezpośredniego zużycia energii w rozpatrywanym kompleksie budowlanym. Dane wejściowe do procedury wyznaczania wskaźników skumulowanego zużycia energii w kompleksie budowlanym stanowią także wskaźniki skumulowanego zużycia energii dla nośników energii dostarczanych do budynku z zewnątrz. Takie podejście jest uzasadnione, ponieważ gospodarka energetyczna kompleksu budowlanego jest powiązana jednostronnie z krajowym systemem energetycznym poprzez dostawę nośników energii do kompleksu budowlanego. W analizowanym przypadku kompleksu budowlanego następujące wartości wskaźników skumulowanego zużycia energii zostały wykorzystane w obliczeniach:

elektryczność: $e_7^* = 3.83 \text{ GJ/ GJ}$

woda wodociągowa: $e_8^* = 0,03122 \text{ GJ/t}$

gaz ziemny: $e_9^* = 1.03 \text{ GJ/ GJ}$

ciepło z sieci ciepłowniczej: $e_{10}^* = 1.23 \text{ GJ/ GJ}$

W przypadku rozpatrywanego budynku układ równań bilansu skumulowanego zużycia energii ma następującą postać:

$$\begin{aligned}
 a_{7\ 1}^D \cdot e_7^* &= e_1^* \\
 a_{7\ 2}^D \cdot e_7^* + a_{10\ 2}^D \cdot e_{10}^* &= e_2^* \\
 a_{7\ 3}^D \cdot e_7^* + a_{8\ 3}^D \cdot e_8^* + a_{10\ 3}^D \cdot e_{10}^* &= e_3^* \\
 a_{7\ 4}^D \cdot e_7^* + a_{10\ 4}^D \cdot e_{10}^* &= e_4^* \\
 a_{1\ 5}^G \cdot e_1^* + a_{2\ 5}^G \cdot e_2^* + a_{7\ 5}^D \cdot e_7^* &= e_5^* \\
 a_{7\ 6}^D \cdot e_7^* &= e_6^*
 \end{aligned}
 \tag{3.6}$$

Tablica 3.5 ujemuje wyniki obliczeń wskaźników skumulowanego zużycia energii dla wszystkich nośników energii w budynku. Wskaźniki $e_1^* \div e_6^*$ dotyczą nośników energii, które są wytwarzane w budynku.

Tablica 3.5. Obliczone wskaźniki skumulowanego zużycia energii w rozpatrywanym budynku

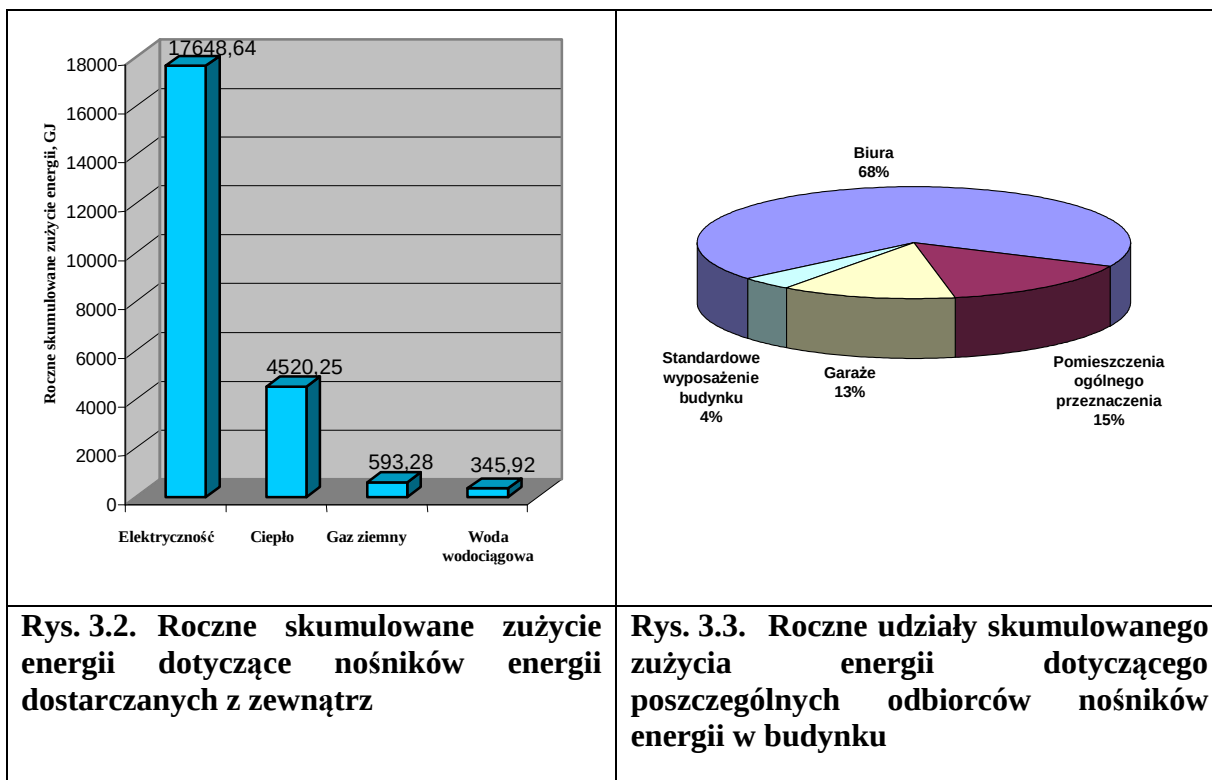
	Nośniki energii	Jed.	Wskaźnik skumulowanego zużycia energii
1	Czynnik chłodzący (woda-glikol) 6/12°C	GJ/GJ	$e_1^* = 1,861$
2	Ciepła woda procesowa 85/55 °C	GJ/GJ	$e_2^* = 1,322$
3	Ciepła woda użytkowa	GJ/t	$e_3^* = 0,2561$
4	Ciepła woda procesowa 60/45 °C	GJ/GJ	$e_4^* = 1,248$
5	Powietrze z centrali klimatyzacyjnej	GJ/t	$e_5^* = 0,03233$
6	Powietrze wyciągowe z garaży	GJ/t	$e_6^* = 0,003411$
7	Energia elektryczna	GJ/GJ	$e_7^* = 3,83$
8	Woda wodociągowa	GJ/t	$e_8^* = 0,03122$
9	Gaz sieciowy	GJ/GJ	$e_9^* = 1,03$
10	Ciepło z sieci ciepłowniczej	GJ/GJ	$e_{10}^* = 1,23$

Wykorzystując wyniki bilansu zużycia energii wyznaczono roczne, sumaryczne zużycie energii pierwotnej (skumulowane zużycie energii):

$$W = D_7 e_7^* + D_8 e_8^* + D_9 e_9^* + D_{10} e_{10}^* \quad (3.7)$$

W analizowanym budynku roczne, sumaryczne zużycie energii pierwotnej wynosi $W=23108 \text{ GJ/a}$. W odniesieniu do powierzchni użytkowej pomieszczeń biurowych (8000 m^2) wskaźnik skumulowanego rocznego zużycia energii wynosi $w=2,889 \text{ GJ/(a m}^2\text{)}$.

Na rysunku 3.2 przedstawiono roczne skumulowane zużycie energii dotyczące nośników energii dostarczanych z zewnątrz. Rysunek 3.3 przedstawia udziały skumulowanego zużycia energii dotyczącego poszczególnych odbiorców nośników energii w budynku (pomieszczenia biurowe, pomieszczenia ogólnego przeznaczenia, garaże oraz standardowe wyposażenie budynku).



3.4. Analiza skumulowanej emisji szkodliwych substancji

Przykładowy bilans skumulowanej emisji substancji szkodliwych został przeprowadzony dla wariantu gospodarki energetycznej rozpatrywanego kompleksu budowlanego z zastosowaniem układu CHP, bazującym na mikroturbinie gazowej. Analizę oparto na przedstawionym w rozdziale 5.3.1. modelu matematycznym obliczania wskaźników skumulowanej emisji substancji szkodliwych. W analizowanym przykładzie obliczeniowym rozpatrzono emisję związków NO_x . Dane wejściowe do tej procedury stanowią wyniki rocznego bilansu bezpośredniego zużycia energii w analizowanym kompleksie

budowlanym, wskaźniki skumulowanej emisji obciążające nośniki energii dostarczane do budynku z zewnątrz oraz wielkości emisji bezpośrednich powstające w procesach należących do poszczególnych gałęzi energetycznych i technologicznych. W analizie uwzględniono efekt zastępowania przez energię elektryczną produkowaną w układzie CHP energii elektrycznej wytwarzanej z tego samego paliwa w elektrowni gazowej. Uwzględniono sprawność transformacji i przesyłania energii elektrycznej do budynku.

Na potrzeby niniejszej analizy określono wskaźniki skumulowanej emisji NO_x dla nośników dostarczanych z zewnątrz do budynku (tablica 3.6). W analizie pominięto emisję związaną z wydobyciem i dostarczaniem gazu ziemnego do budynku. Na podstawie analizy procesowej określono wskaźniki bezpośredniej emisji w gałęziach gospodarki energetycznej budynku. Bezpośrednia emisja substancji szkodliwych w podsystemie energetycznym analizowanego kompleksu budowlanego ma miejsce w układzie skojarzonym ciepło-elektrycznym oraz w gazowym kotle szczytowym.

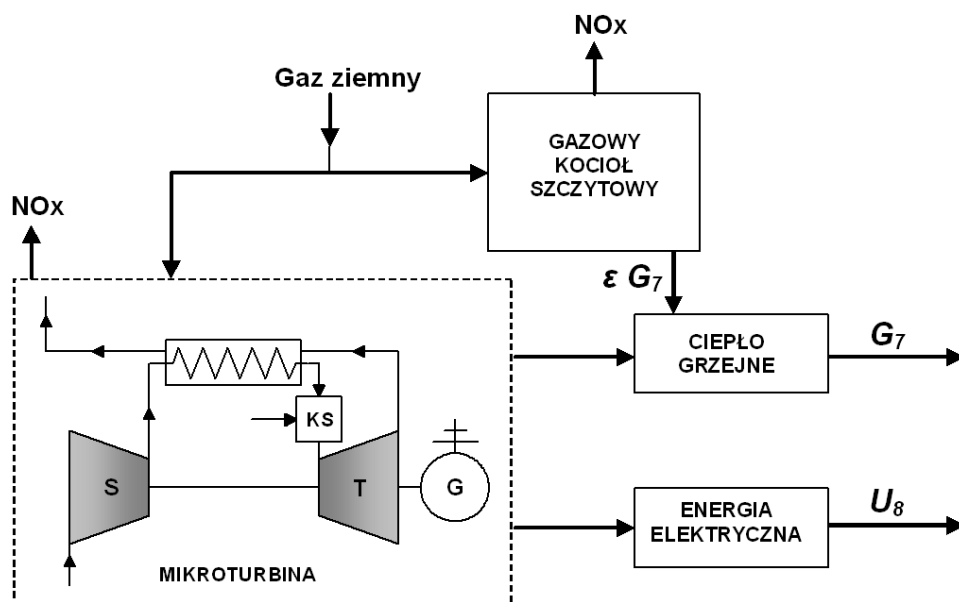
Dla układu CHP wartość wskaźnika bezpośredniej emisji NO_x przyjęto na poziomie 0,0884 kg/GJ_c (dane producenta). W przypadku kotła szczytowego wzięto pod uwagę następującą wartość tego wskaźnika (dane producenta): 0,005556 kg/GJ_c. Wszystkie dane wejściowe do analizy zebrano w tablicy 3.6.

Tablica 3.6. Dane wejściowe do analizy skumulowanej emisji zanieczyszczeń dla analizowanego budynku

Wskaźnik skumulowanej emisji NO _x dla energii elektrycznej wytwarzanej w elektrowni gazowej	$p_{delg}^* = 0,136 \text{ (kg/GJ}_{el})$
Wskaźnik skumulowanej emisji NO _x dla energii elektrycznej wytwarzanej w elektrowni systemowej	$p_{dels}^* = 0,4861 \text{ (kg/GJ}_{el})$
Wskaźnik skumulowanej emisji NO _x dla pozyskania i dostarczenia do budynku wody wodociągowej	$p_{dw}^* = 0,003936 \text{ (kg/Mg)}$
Wskaźnik bezpośredniej emisji NO _x dla układu CHP	$p_{bCHP} = 0,0884 \text{ kg/GJ}_c$
Wskaźnik bezpośredniej emisji NO _x dla gazowego kotła szczytowego	$p_{bksz} = 0,005556 \text{ kg/GJ}_c$
Roczna produkcja ciepła w układzie CHP	$Q_{CHP} = 3308 \text{ GJ/rok}$
Roczna produkcja ciepła szczytowego w budynku	$Q_{ksh} = 367,6 \text{ GJ/rok}$
Roczna uboczna wytwórczość energii elektrycznej w układzie CHP	$U_g = 2150 \text{ GJ/rok}$
Zapotrzebowanie na ciepło dla budynku	$Q = 3675,66 \text{ GJ/rok}$

Wskaźnik skojarzenia w układzie CHP	$\sigma=0,65$
Sprawność energetyczna układu CHP	$\eta_{E\,CHP} = 0,77$
Sprawność energetyczna gazowego kotła szczytowego	$\eta_{E\,k\,sz} = 0,85$
Udział ciepła szczytowego w całkowitej produkcji ciepła	$\varepsilon=0,1$
Sprawność energetyczna ciepłowni zasilanej gazem ziemnym	$\eta_{E\,c\,g} = 0,85$
Sprawność energetyczna zastąpionej elektrowni zasilanej gazem ziemnym	$\eta_{E\,el\,g} = 0,339$

W rozważanym przypadku ma miejsce uboczne wytwarzanie energii elektrycznej w układzie CHP. Założono, że ciepło jest produktem głównym. Dlatego też, obciążenie ciepła emisjami substancji szkodliwych powinno być pomniejszone o emisję związaną z zastąpieniem produkcji elektryczności dostawą z systemu elektroenergetycznego. Przykład wykonano dla przypadku emisji NOx. Schemat bilansu skumulowanej emisji NOx związany z gałęzią energetyczną odpowiedzialną za produkcję ciepła w budynku przedstawiono na rys. 3.4.



Rys. 3.4. Schemat bilansu bezpośredniej emisji NOx w gałęzi energetycznej budynku odpowiedzialnej za produkcję ciepła ($j=7$)

Układu równań bilansu skumulowanej emisji NOx dla rozważanego przykładu:

$$\begin{aligned}
a_{8,1} p_{8G}^* &= p_{1G}^* \\
a_{7,2} p_{7G}^* + a_{8,2} p_{8G}^* &= p_{2G}^* \\
a_{7,3} p_{7G}^* + a_{8,3} p_{8G}^* + a_{10,3} p_{10G}^* &= p_{3G}^* \\
a_{7,4} p_{7G}^* + a_{8,4} p_{8G}^* &= p_{4G}^* \\
a_{1,5} p_{1G}^* + a_{2,5} p_{2G}^* + a_{8,5} p_{8G}^* &= p_{5G}^* \\
a_{8,6} p_{8G}^* &= p_{6G}^* \\
\frac{P_{b7}}{G_7} + a_{9,7} p_{9D}^* &= p_{7G}^* + \frac{U_{87}}{G_7} p_{delg}^* \\
p_{8G}^* &= \frac{U_8 p_{delg}^* + D_8 p_{dels}^*}{U_{87} + D_8} \\
p_{9D}^* &= 0 \\
p_{10D}^* &= 0,003936
\end{aligned}$$

gdzie a_{ij} - wskaźniki zużycia poszczególnych nośników energii, p_i^* - wskaźnik skumulowanej emisji dla nośników energii w budynku, P_{b7} - roczna bezpośrednia emisja NOx w gałęzi 7, G_7 - produkcja ciepła grzeijnego, U_{87} - produkcja uboczna energii elektrycznej, D_8 - dostawa energii elektrycznej z systemem elektroenergetycznym.

Wskaźniki skumulowanej emisji dla poszczególnych nośników energii zebrano w tablicy 3.7.

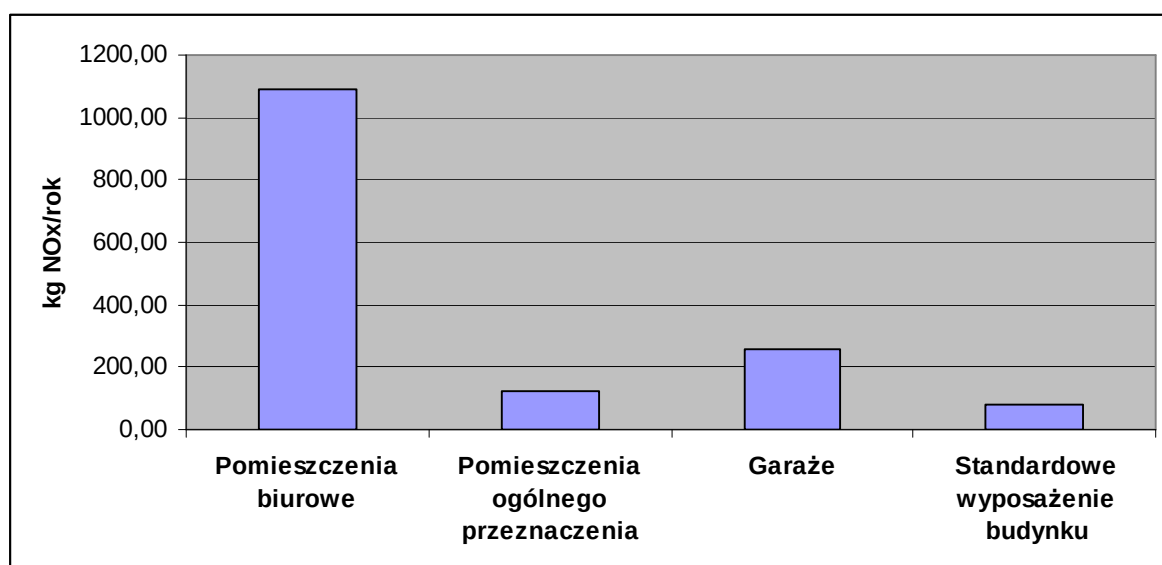
Tablica 3.7. Wskaźniki skumulowanej emisji związków NOx dla nośników energii w analizowanym kompleksie budowlanym

lp.	Nośnik energii	JED.	NOx
1	Czynnik chłodzący 6/12 °C	kg/GJ	0,1578
2	Gorąca woda procesowa 85/45 °C	kg/GJ	0,008403
3	CWU	kg/Mg	0,005216
4	Gorąca woda procesowa 60/45 °C	kg/GJ	0,002091
5	Powietrze z centrali klimatyzacyjnej	kg/Mg	0,001408
6	Powietrze wentylacyjne	kg/Mg	0,0002891
7	Ciepło grzejne	kg/GJ	0,0005652
8	Energia elektryczna	kg/GJ	0,3248
9	Gaz ziemny	kg/Mg	0
10	Woda wodociągowa	kg/Mg	0,003936

W tablicy 3.8 oraz na rys. 3.5 zebrano wielkości obciążenia emisjami NOx dla wszystkich odbiorców w analizowanym budynku.

Tablica 3.8. Roczne obciążenie skumulowaną emisją NO_x podsystemu odbiorców (kg NO_x/rok)

		Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodzący 6/12 °C	167,04	0,00	0,00	0,00
2	Gorąca woda procesowa 85/45 °C	0,00	7,16	0,00	0,00
3	CWU	0,00	5,19	0,00	0,00
4	Gorąca woda procesowa 60/45 °C	3,51	0,00	0,00	0,00
5	Powietrze z centrali klimatyzacyjnej	64,13	42,75	0,00	0,00
6	Powietrze wentylacyjne	0,00	0,00	125,93	0,00
7	Ciepło grzejne	0,00	0,00	0,00	0,00
8	Energia elektryczna	857,22	25,73	129,05	80,13
9	Gaz ziemny	0,00	0,00	0,00	0,00
10	Woda wodociągowa	0,00	39,69	0,00	0,00
	Suma	1091,90	120,52	254,98	80,13



Rys. 3.5. Roczne emisje NO_x obciążające podsystem odbiorców analizowanego budynku

3.5. Analiza termoeekologiczna

Model matematyczny bilansu kosztu termoeologicznego opisany w punkcie 2.4 został wykorzystany do analizy ekologicznej przykładowego kompleksu budowlanego, którego gospodarkę energetyczną opisano w punkcie 2.1. Dane wejściowe do procedury wyznaczania wskaźników kosztu termoeologicznego wynikają z bilansu bezpośredniego zużycia energii kompleksu budowlanego oraz ze wskaźników kosztu termoeologicznego dla nośników energii, które są dostarczane z zewnątrz. Takie podejście jest uzasadnione, tak jak w przypadku analizy skumulowanego zużycia energii, ponieważ gospodarka energetyczna kompleksu budowlanego jest powiązana z krajowym systemem energetycznym tylko poprzez dostawę nośników energii z tego systemu do kompleksu budowlanego. Nie ma silnych powiązań odwrotnych. W przypadku analizowanego budynku wzięto pod uwagę następujące wartości wskaźników kosztu termoeologicznego dotyczące nośników dostarczanych z zewnątrz:

elektryczność: 3,6 MJ/MJ_{el},

woda wodociągowa: 0,008 GJ/t,

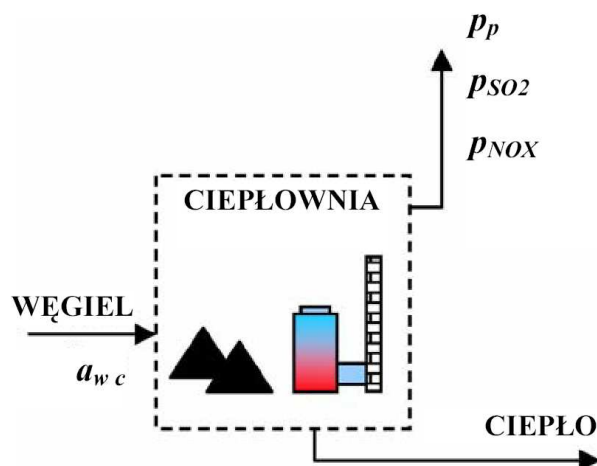
gaz ziemny: 714,8 MJ/kmol.

Brakujący wskaźnik kosztu termoeologicznego dostarczanego ciepła został wyznaczony zgodnie z równaniem bilansu kosztu termoeologicznego (2.25). Założono dostarczanie ciepła z ciepłowni opalanej węglem. Średnie zużycie węgla w ciepłowni określono w oparciu o założoną sprawność energetyczną ciepłowni na poziomie $\eta_{Ec}=0,8$. Do obliczeń przyjęto następujące dane:

- emisja substancji szkodliwych: $p_{SO_2}=0,0008125$ kg /MJ_c; $p_{NO_x}=0,0000375$ kg /MJ_c; $p_p=0,00175$ kg pyłu/MJ_c,
- wskaźnik zużycia węgla na jednostkę produkowanego ciepła w ciepłowni: $a_{wc}=0,05435$ kg/MJ_c,
- wskaźnik kosztu termoeologicznego wydobycia i dostarczenia węgla: $\rho_w=27,2$ MJ/MJ.

Zgodnie z równaniem (2.25) wskaźnik kosztu termoeologicznego ciepła produkowanego w ciepłowni węglowej można wyrazić za pomocą wzoru:

$$\rho_c = a_{wc}\rho_c + \sum_k p_{kc}\zeta_k \quad (3.8)$$



Rys. 3.6. Bilans kosztu termoeekologicznego dla ciepłowni węglowej

Równanie bilansowe (3.8) zostało zobrazowane na rys. 3.6. Wskaźnik ζ_k opisuje skumulowane zużycie nieodnawialnych zasobów energii związane z kompensacją emisji substancji szkodliwych:

$$\zeta_{SO_2} = 49.3 \text{ MJ} / \text{kg}_{SO_2}$$

$$\zeta_{NO_x} = 49.3 \text{ MJ} / \text{kg}_{NO_x}$$

$$\zeta_p = 10.19 \text{ MJ} / \text{kg}_p$$

Wskaźnik kosztu termoeekologicznego produkcji ciepła w ciepłowni węglowej:

$$\rho_c = 1.538 \text{ MJ} / \text{MJ}_c$$

Sprawność przesyłania ciepła z ciepłowni do budynku za pomocą sieci ciepłowniczej przyjęto na poziomie:

$$\eta_{pc} = 0.85$$

Koszt termoeekologiczny ciepła dostarczanego do budynku:

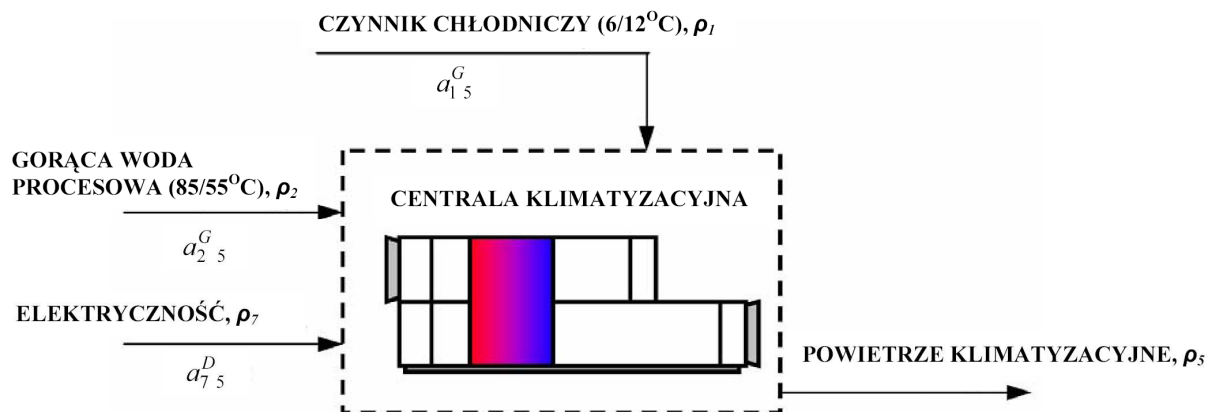
$$\rho_{lo} = 1.8 \text{ MJ} / \text{MJ}_c$$

W analizowanym kompleksie budowlanym nie zachodzą procesy spalania paliw w celu wytworzenia nośników energii. Dlatego też wewnątrz osłony bilansowej rozpatrywanego budynku produkcja nośników energii nie jest obciążona generowaniem produktów odpadowych $\sum_k p_{kj} \zeta_k$.

Gaz ziemny jest zużywany tylko w celu przygotowania posiłków w pomieszczeniach ogólnego przeznaczenia. W przypadku analizowanego budynku układ równań bilansowych kosztu termoeologicznego jest wyrażony następująco:

$$\begin{aligned}
 \rho_1 &= a_{7\ 1}^D \cdot \rho_7 \\
 \rho_2 &= a_{7\ 2}^D \cdot \rho_7 + a_{10\ 2}^D \cdot \rho_{10} \\
 \rho_3 &= a_{7\ 3}^D \cdot \rho_7 + a_{8\ 3}^D \cdot \rho_8 + a_{10\ 3}^D \cdot \rho_{10} \\
 \rho_4 &= a_{7\ 4}^D \cdot \rho_7 + a_{10\ 4}^D \cdot \rho_{10} \\
 \rho_5 &= a_{1\ 5}^G \cdot \rho_1 + a_{2\ 5}^G \cdot \rho_2 + a_{7\ 5}^D \cdot \rho_7 \\
 \rho_6 &= a_{7\ 6}^D \cdot \rho_7
 \end{aligned}
 \tag{3.9}$$

Na rysunku 3.7 pokazano przykład bilansu kosztu termoeologicznego dla jednej z gałęzi energetycznych (centrala klimatyzacyjna, j=5) W tablicy 3.9 ujęto obliczone wskaźniki kosztu termoeologicznego dla nośników energii w rozpatrywanym budynku.



Rys. 3.7. Przykład bilansu kosztu termoeologicznego dla jednej z gałęzi energetycznych (j=5)

Na podstawie rezultatów bilansu kosztu termoeologicznego w podsystemie energetycznym wyznaczono roczny koszt termoeologiczny (rys. 3.8, tablica 3.10) dla wszystkich odbiorców nośników energii w budynku (pomieszczenia biurowe, pomieszczenia ogólnego przeznaczenia, garaże oraz system standardowego wyposażenia budynku). W tym przypadku wzięto pod uwagę dodatkowy koszt termoeologiczny wynikający z emisji zanieczyszczeń generowanych wskutek spalania gazu ziemnego

w pomieszczeniach ogólnego przeznaczenia. W tym celu uwzględniono następujące wskaźniki emisji:

$$p_{\text{SO}_2} = 0 \text{ kg/MJ}_g,$$

$$p_{\text{NO}_x} = 0.00003 \text{ kg/MJ}_g,$$

$$p_p = 0 \text{ kg/MJ}_g.$$

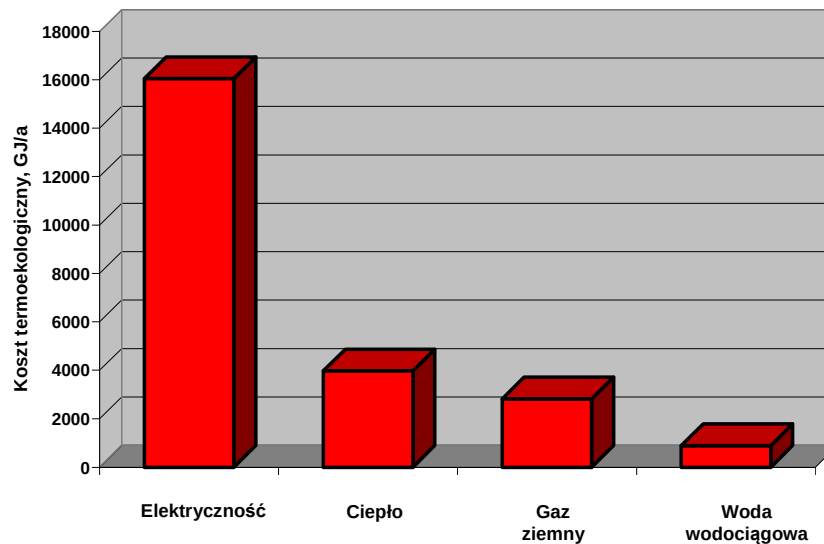
Tablica 3.9. Wyniki przykładowych obliczeń kosztu termoeekologicznego dla wszystkich nośników energii w budynku

	Nośniki energii	Jed.	Koszt termoeekologiczny
1	Czynnik chłodzący (woda-glikol) 6/12 °C	MJ/MJ	1,647
2	Ciepła woda procesowa 85/55 °C	MJ/MJ	1,887
3	Ciepła woda użytkowa	GJ/t	0,33
4	Ciepła woda procesowa 60/45 °C	MJ/MJ	1,816
5	Powietrze z centrali klimatyzacyjnej	GJ/t	0,0386
6	Powietrze wyciągowe z garaży	GJ/t	0,0032
7	Energia elektryczna	MJ/MJ	3,6
8	Woda wodociągowa	GJ/t	0,008
9	Gaz ziemny sieciowy *)	GJ/kmol	0,7148
10	Ciepło z sieci ciepłowniczej	MJ/MJ	1,8

*) Średnioważona wartość wskaźnika kosztu termoeekologicznego uwzględniająca wydobycie własne i import.

Tablica 3.10. Wyniki przykładowych obliczeń kosztu termoeekologicznego w podsystemie odbiorców

Odbiorca	Roczny koszt termoeekologiczny
Pomieszczenia biurowe	16048 GJ/a
Pomieszczenia ogólnego przeznaczenia	3975 GJ/a
Garaże	2824 GJ/a
Standardowe wyposażenie budynku	888 GJ/a



Rys. 3.8. Roczny koszt termoeekologiczny w podsystemie odbiorców analizowanego budynku

Roczny koszt termoeekologiczny dostaw nośników energii z zewnątrz (łącznie z wodą wodociągową) wynosi 23735 GJ/rok, co w odniesieniu do jednostki powierzchni użytkowej kompleksu budowlanego daje wskaźnik 2,97 GJ/(m² rok).

4. Algorytmu doboru struktury gospodarki energetycznej kompleksu budowlanego użyteczności publicznej

4.1. Procedura generacji wariantów gospodarki energetycznej kompleksu budowlanego

Procedura doboru struktury gospodarki energetycznej kompleksu budowlanego została opracowana na podstawie modelu przepływów międzygałęziowych nośników energii. Dobór struktury gospodarki energetycznej w fazie projektu wstępnego kompleksu budowlanego polega na utworzeniu optymalnego zbioru maszyn i urządzeń energetycznych oraz na określeniu powiązań pomiędzy nimi wynikających z przepływów nośników energii. W pierwszej kolejności dokonuje się wyboru dostępnych technologii produkcji nośników energii. Na tej podstawie opracowuje się scenariusze gospodarki energetycznej dla narzuconego układu podsystemu odbiorców nośników energii. Scenariusz to słowny opis sposobów realizacji gospodarki energetycznej odnoszący się do rozpatrywanego kompleksu budowlanego scharakteryzowanego przez wektor zapotrzebowania nośników energii do podsystemu odbiorców. Kolejnym krokiem jest opracowanie uniwersalnej listy nośników energii ujmującej produkcję główną nośników energii, produkcję uboczną oraz dostawy z zewnątrz. Uniwersalna lista nośników energii zawiera nośniki, których wytwórczość wynika z zapotrzebowania podsystemu odbiorców z uwzględnieniem nośników energii wytwarzanych w wyniku powiązań międzygałęziowych w podsystemie energetycznym. Nośniki energii umieszczone na uniwersalnej liście można podzielić na dwie grupy:

- nośniki wytwarzane w podsystemie energetycznym jako produkty główne,
- nośniki energii wytwarzane ubocznie w podsystemie energetycznym, które nie uzupełniają produkcji głównej oraz dostawy zewnętrzne (uzupełniające i wyłączne).

Nośniki energii na uniwersalnej liście opisuje się za pomocą binarnych wektorów określających czy dany nośnik energii jest wytwarzany jako produkt główny (wektor $\mathbf{B}_G^b$), czy jest on dostarczany z zewnątrz (wektor $\mathbf{B}_D^b$) oraz czy jest zużywany bezpośrednio w podsystemie odbiorców (wektor $\mathbf{O}^b$).

Obok uniwersalnej listy nośników energii występujących w kompleksie budowlanym tworzy się bazę wiedzy o technologiach energetycznych i chłodniczych stosowanych w budynkach. Baza wiedzy o technologiach energetycznych stanowi podstawę do określenia

współczynników macierzy „input-output” charakterystycznej dla tablicy przepływów międzygałęziowych.

Na tym etapie strukturę podsystemu energetycznego można przedstawić w postaci ideowego schematu obliczeniowego i odpowiadającego mu grafu skierowanego. Strukturę podsystemu energetycznego można również opisać za pomocą binarnej macierzy powiązań międzygałęziowych. Macierz binarna jest wykorzystywana do tworzenia tablicy powiązań międzygałęziowych nośników energii w kompleksie budowlanym. Tablica ta stanowi podstawę modelu matematycznego bilansu gospodarki energetycznej kompleksu budowlanego.

Każdemu nośnikowi energii wytwarzanemu jako produkt główny odpowiada temat projektowy. Z tematem projektowym jest związany podzbiór rozwiązań technicznych. Przez rozwiązanie techniczne rozumie się zbiór urządzeń i instalacji energetycznych realizujących produkcję określonego nośnika energii. Jednemu tematowi projektowemu może odpowiadać kilka rozwiązań technicznych. Na przykład produkcja ciepła w kompleksie budowlanym może być realizowana w układzie skojarzonym ciepłno-elektrycznym, w ciepłowniczych kotłach wodnych bądź w nowoczesnej instalacji ogniwa paliwowego. Zbiór tematów projektowych i rozwiązań technicznych najdogodniej jest przedstawić w formie binarnej macierzy tematów i rozwiązań technicznych **II**. Macierz **II** zawiera wszystkie tematy projektowe oraz rozwiązania techniczne, w których przewiduje się określone urządzenia energetyczne bądź możliwość dostawy nośników energii z zewnątrz. Poszczególne wiersze macierzy odpowiadają danemu rozwiązaniu technicznemu, a kolumny określone urządzeniu energetycznemu.

Każde rozwiązanie techniczne jest opisane za pomocą binarnych macierzy powiązań

$\mathbf{A}_p^b = [\mathbf{a}_{p\ ij}^b]$ oraz $\mathbf{F}_p^b = [\mathbf{f}_{p\ ij}^b]$, których elementy definiuje się następująco:

$\mathbf{a}_{p\ ij}^b = 1$ - jeżeli i -ty nośnik energii jest zużywany w p -tym rozwiązaniu technicznym przy produkcji j -tego nośnika energii,

$\mathbf{a}_{p\ ij}^b = 0$ - jeżeli i -ty nośnik energii nie jest zużywany w p -tym rozwiązaniu technicznym przy produkcji j -tego nośnika energii,

$\mathbf{f}_{p\ ij}^b = 1$ - jeżeli i -ty nośnik energii jest wytwarzany ubocznie w p -tym rozwiązaniu technicznym przy produkcji j -tego nośnika energii,

$\mathbf{f}_{p\ ij}^b = 0$ - jeżeli i -ty nośnik energii nie jest wytwarzany ubocznie w p -tym rozwiązaniu technicznym przy produkcji j -tego nośnika energii.

gdzie:

$p=1,2, \dots, m$

$i=1,2, \dots, n$

$j=1,2, \dots, n_g$

m – liczba rozwiązań technicznych,

n – liczba nośników energii tworzących listę uniwersalną,

n_g – liczba nośników energii wytwarzanych jako produkty główne.

Jeżeli w rozwiązaniu technicznym występuje urządzenie podstawowe i szczytowe wówczas macierze binarne $\mathbf{A}_p^b$ i $\mathbf{F}_p^b$ wyznacza się sumując zgodnie z zasadami algebry Boole’a macierze binarne opisujące zużycie i uboczne wytwarzanie nośników energii w urządzeniu podstawowym i szczytowym:

$$\mathbf{A}_p^b = \mathbf{A}_{p\ P}^b + \mathbf{A}_{p\ G}^b \quad (4.1)$$

$$\mathbf{F}_p^b = \mathbf{F}_{p\ P}^b + \mathbf{F}_{p\ G}^b \quad (4.2)$$

Na podstawie macierzy $\mathbf{A}_p^b$ tworzy się macierz binarną $\mathbf{Z}^b$ określającą strukturę zużycia nośników energii w zbiorze rozwiązań technicznych:

$$\mathbf{Z}^b = [\mathbf{A}_1^b \mathbf{E}_0, \dots, \mathbf{A}_p^b \mathbf{E}_0, \dots, \mathbf{A}_m^b \mathbf{E}_0] \quad (4.3)$$

gdzie $\mathbf{E}_0$ oznacza wektor kolumnowy o n_g elementach jedynekowych. Operacja mnożenia macierzy $\mathbf{A}_p^b$ przez wektor $\mathbf{E}_0$ zachodzi zgodnie z zasadami algebry Boole’a.

Jak wspomniano, każdemu tematowi projektowemu przypisuje się nośnik energii wytwarzany jako produkt główny. Wybierając po jednym rozwiązaniu technicznym z każdego tematu projektowego tworzy się zbiór wszystkich możliwych do zrealizowania wariantów struktury gospodarki energetycznej, które podlegają dalszej analizie w celu wyboru wariantu optymalnego. Liczba wszystkich możliwych wariantów gospodarki energetycznej wynosi:

$$N = \prod_{t=1}^s m_t \quad (4.4)$$

gdzie:

t – kolejny numer tematu projektowego,

m_t – liczba rozwiązań technicznych w t -tym temacie projektowym,

s – liczba tematów projektowych.

W celu wyszukania wszystkich możliwych wariantów struktury gospodarki energetycznej tworzy się binarny wektor kolumnowy $\mathbf{W}_l^b$, który zdefiniowany jest następująco:

$w_{p1} = 1$ - jeżeli p -te rozwiązanie techniczne należy do l -tego wariantu struktury gospodarki energetycznej,

$w_{p1} = 0$ - jeżeli p -te rozwiązanie techniczne nie należy do l -tego wariantu struktury gospodarki energetycznej,

gdzie: $l=1, 2, \dots, N$ oznacza kolejny numer wariantu struktury gospodarki energetycznej kompleksu budowlanego.

Zasada tworzenia wektora $\mathbf{W}_l^b$ dla każdego wariantu gospodarki energetycznej polega na przypisaniu jednego rozwiązania technicznego każdemu tematowi projektowemu. Wyznaczona w ten sposób liczba możliwych do zrealizowania wariantów gospodarki energetycznej kompleksu budowlanego jest z reguły bardzo duża a duża część z określonych wariantów nie jest ekonomicznie uzasadniona. Przykładem takiego wariantu może być wariant, w którym produkcja energii elektrycznej i ciepła ma miejsce w kilku układach CHP bazujących na różnych technologiach. Na przykład układ CHP z tłokowym silnikiem spalinowym współpracujący z układem CHP działającym w oparciu o ogniwo paliwowe. W tym przypadku są to dwie różne technologie skojarzonego wytwarzania ciepła i elektryczności. Nie wyklucza się tutaj układów hybrydowych opisanych w rozdziale 4.4. Mimo, iż gospodarka energetyczna współczesnych kompleksów budowlanych jest coraz bardziej złożona to z reguły zamawiający decyduje się na jedną technologię wytwarzania ciepła i elektryczności w skojarzeniu. Stosuje się wprowadzić we współczesnych kompleksach budowlanych połączenie równoległe kilku jednostek CHP niemniej jednak działają one w oparciu o tę samą technologię. Te uwagi nie dotyczą przypadków wytwarzania nośników energii w urządzeniach podstawowych i szczytowych. Aby wykluczyć z dalszych rozważań takie przypadki (np. połączenia różnych technologii skojarzonej gospodarki ciepłno-elektrycznej) można przeprowadzić ich eliminację ze zbioru wszystkich wariantów gospodarki energetycznej budynku za pomocą tzw. kryterium zgodności technologii. W tym celu tworzy się binarny wektor kolumnowy $\mathbf{L}_h^b$ określający grupy urządzeń energetycznych wytwarzających te same nośniki energii w oparciu o różne technologie. Wektor ten definiuje się następująco:

$L_{uh} = 1$ - jeżeli u -te urządzenie energetyczne należy do h -tej grupy urządzeń

wytwarzających te same nośniki energii w oparciu o różne technologie,

$L_{uh}=0$ - jeżeli u -te urządzenie energetyczne nie należy do h -tej grupy urządzeń wytwarzających te same nośniki energii w oparciu o różne technologie.

W celu identyfikacji wszystkich nośników energii wytwarzanych wspólnie z innymi nośnikami w jednym urządzeniu energetycznym tworzy się binarny wektor kolumnowy M_s^b . Elementy tego wektora określone są następująco:

$M_{is}=1$ - jeżeli i -ty nośnik energii należy do s -tej grupy nośników energii wytwarzanych wspólnie z innymi nośnikami w jednym urządzeniu energetycznym,

$M_{is}=0$ - jeżeli i -ty nośnik energii nie należy do s -tej grupy nośników energii wytwarzanych wspólnie z innymi nośnikami w jednym urządzeniu energetycznym,

Bazując na wektorach L_h^b i M_s^b przeprowadza się eliminację wszystkich wariantów gospodarki energetycznej, które nie spełniają kryterium zgodności technologii aktualizując w ten sposób bazę wariantów Π .

Pomimo weryfikacji wariantów za pomocą wektorów L_h^b i M_s^b poszczególne wektory W_l^b wariantów mogą zawierać rozwiązania zbędne dla zapewnienia pokrycia zapotrzebowania na nośniki energii w podsystemie odbiorców. Na przykład rezygnacja z chłodziarki absorpcyjnej na rzecz agregatu sprężarkowego prowadzi do braku zapotrzebowania na gorącą wodę zasilającą tę chłodziarkę. W takich przypadkach zbędne rozwiązania techniczne produkujące nośniki energii, które nie są zużywane na potrzeby podsystemu energetycznego i podsystemu odbiorców są eliminowane z wektorów wariantów struktury gospodarki energetycznej budynku. W tym celu mnoży się według zasad algebry Boole'a macierz Z^b przez wektor W_l^b danego wariantu uzyskując w ten sposób wektor Y_l^b . Wektor Y_l^b określa zapotrzebowanie na poszczególne nośniki energii wynikające wyłącznie z potrzeb podsystemu energetycznego w danym wariantcie gospodarki energetycznej. W kolejnym kroku do wektora Y_l^b dodaje się stosując algebrę Boole'a wektor O^b zapotrzebowania na nośniki energii w podsystemie odbiorców. Uzyskuje się w ten sposób wektor X_l^b określający, które nośniki energii są zużywane w

danym wariantcie. Wektor $\mathbf{X}_1^b$ porównuje się z wektorem $\mathbf{W}_1^b$ rozpatrywanego wariantu otrzymując informację o tym, czy w danym wariantcie są brane pod uwagę nośniki energii, które nie są zużywane ani w podsystemie energetycznym ani w podsystemie odbiorców. Jeśli wektor $\mathbf{X}_1^b$ zawiera element zerowy dla danego nośnika energii a równocześnie z analizy wektora $\mathbf{W}_1^b$ wynika, że ujmuje on rozwiązanie techniczne związane z wytwarzaniem bądź dostawę tego nośnika energii oznacza to, że należy takie rozwiązanie techniczne z danego wariantu wykluczyć.

Wynikowe, binarne macierze powiązań opisujące strukturę gospodarki energetycznej kompleksu budowlanego $\mathbf{A}_P^b$, $\mathbf{A}_G^b$, $\mathbf{F}_P^b$, $\mathbf{F}_G^b$ wyznacza się na podstawie relacji:

$$\mathbf{A}_P^b = \Phi_P \mathbf{W}_1, \quad (4.5)$$

$$\mathbf{A}_G^b = \Phi_G \mathbf{W}_1, \quad (4.6)$$

$$\mathbf{F}_P^b = \Psi_P \mathbf{W}_1, \quad (4.7)$$

$$\mathbf{F}_G^b = \Psi_G \mathbf{W}_1, \quad (4.8)$$

przy czym:

$$\Phi_P = [\mathbf{A}_{1P}^b, \dots, \mathbf{A}_{pP}^b, \dots, \mathbf{A}_{mP}^b], \quad (4.9)$$

$$\Phi_G = [\mathbf{A}_{1G}^b, \dots, \mathbf{A}_{pG}^b, \dots, \mathbf{A}_{mG}^b], \quad (4.10)$$

$$\Psi_P = [\mathbf{F}_{1P}^b, \dots, \mathbf{F}_{pP}^b, \dots, \mathbf{F}_{mP}^b], \quad (4.11)$$

$$\Psi_G = [\mathbf{F}_{1G}^b, \dots, \mathbf{F}_{pG}^b, \dots, \mathbf{F}_{mG}^b]. \quad (4.12)$$

gdzie binarne macierze powiązań międzygałęziowych $\mathbf{A}_{pP}^b$, $\mathbf{A}_{pG}^b$, $\mathbf{F}_{pP}^b$ oraz $\mathbf{F}_{pG}^b$ stanowiące bazę danych, określają strukturę zapotrzebowania i ubocznego wytwarzania nośników energii dla poszczególnych rozwiązań projektowych dotyczących urządzeń podstawowych i szczytowych.

Macierz binarną powiązań międzygałęziowych $\mathbf{A}^b + \mathbf{F}^b$ wyznacza się z relacji:

$$\mathbf{A}^b + \mathbf{F}^b = \mathbf{A}_P^b + \mathbf{A}_G^b + \mathbf{F}_P^b + \mathbf{F}_G^b \quad (4.13)$$

Sumowanie odbywa się zgodnie z zasadami algebry Boole'a.

Dobór struktury gospodarki energetycznej w fazie projektu wstępnego spełnia bardzo ważną rolę. Jakość projektu końcowego zależy od przyjętych na tym etapie rozwiązań technicznych (urządzeń energetycznych i instalacji). Popełnione błędy w doborze struktury mają bardzo duży wpływ na zwiększenie nakładów inwestycyjnych oraz niewłaściwe funkcjonowanie podsystemu energetycznego projektowanego budynku. Tradycyjna metoda projektowania gospodarki energetycznej kompleksu budowlanego opiera się na doświadczeniu zespołu projektującego. Najczęściej ogranicza się ona do rozpatrzenia kilku wariantów gospodarki energetycznej i wyboru najlepszego z nich. Ze względu na postępujący rozwój techniczny urządzeń oraz instalacji energetycznych stosowanych we współczesnych kompleksach budowlanych takie podejście nie jest już obecnie wystarczające. Procedura doboru struktury gospodarki energetycznej kompleksu budowlanego powinna być oparta o metodę systematycznego przeglądu dopuszczalnych struktur, która polega na analizie całkowitego zbioru możliwych do zrealizowania wariantów.

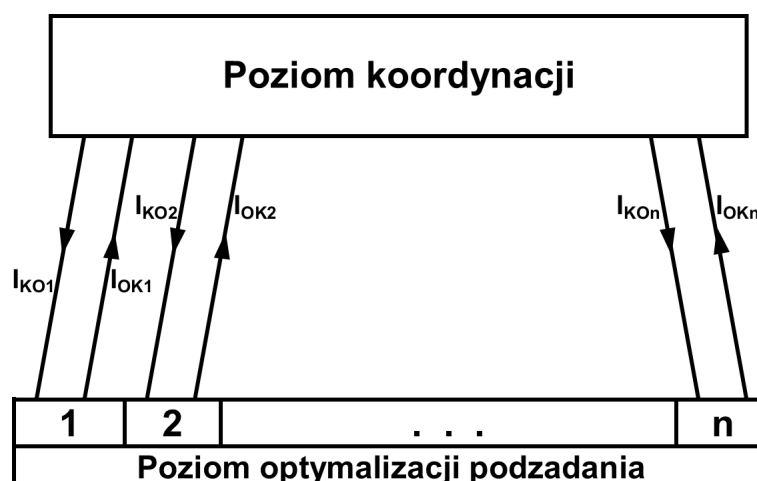
4.2. Dobór optymalnej struktury gospodarki energetycznej kompleksu budowlanego metodą dekompozycji globalnego zadania optymalizacyjnego

4.2.1. Zagadnienie dekompozycji

Metoda dekompozycji polega na podziale globalnego zadania optymalizacyjnego na szereg podzadań rozwiązywanych niezależnie (autonomicznie), a następnie podlegających koordynacji. Dla dekompozycji istotny jest stopień spójności systemu. Od niego bowiem zależy wielkość zadania koordynacyjnego. W metodzie dekompozycji wykorzystuje się cechę hierarchiczności charakterystyczną dla dużych systemów energetycznych, do których należy gospodarka energetyczna kompleksu budowlanego. Zagadnienie dekompozycji jest związane z następującymi problemami:

- wydzielenie oddzielnych podzadań,
- sformułowanie algorytmów optymalizacyjnych poszczególnych podzadań w postaci dogodnej do koordynacji,
- zbudowanie procedury koordynacyjnej.

Na Rys. 4.1. przedstawiono ideę metody dekompozycji globalnego zadania optymalizacyjnego.



Rys. 4.1. Idea metody dekompozycji globalnego zadania optymalizacyjnego

Aby autonomiczne kryteria optymalizacyjne na dowolnym poziomie hierarchii były zgodne z kryterium globalnym, z poziomu koordynacji jest przekazywany zbiór informacji $\{I_{KO1}, I_{KO2}, \dots, I_{KOn}\}$ na poziom optymalizacji autonomicznej poszczególnych podzadań. Po przeprowadzeniu autonomicznej optymalizacji dla każdego podsystemu przesyłany jest na górny poziom hierarchii zbiór informacji $\{I_{OK1}, I_{OK2}, \dots, I_{OKn}\}$ stanowiącej wynik autonomicznej optymalizacji. Na górnym poziomie hierarchii rozpoczyna się wówczas kolejna iteracja, której rezultatem jest poprawiony zbiór parametrów $\{I_{KOi}\}$ podlegający przesyłaniu na dolny poziom optymalizacji. Tak więc metoda dekompozycji jest procedurą iteracyjną. Dla każdego rozwiązania na górnym poziomie hierarchii jest wymagana korekta rozwiązań na dolnym poziomie i odwrotnie. Liczba iteracji zależy od stopnia szczegółowości modelu matematycznego, od dokładności informacji wejściowej i od dokładności metod optymalizacji. Jedną z najbardziej efektywnych metod dekompozycji jest metoda Lagrange’a.

4.2.2. Model matematyczny optymalizacyjny doboru struktury podsystemu energetycznego kompleksu budowlanego

Celem projektu wstępnego jest wybór optymalnego wariantu struktury gospodarki energetycznej kompleksu budowlanego. Pod wyborem struktury jest rozumiany dobór rodzaju i liczby maszyn oraz urządzeń energetycznych, jak również powiązań między nimi. Kryterium doboru optymalnej struktury gospodarki energetycznej stanowi żądanie

maksymalizacji rocznego efektu ekonomicznego działania kompleksu budowlanego. Dla założonego zapotrzebowania podsystemu odbiorców na energię kryterium to sprowadza się do minimalizacji rocznych kosztów działania podsystemu energetycznego kompleksu budowlanego. Funkcja celu ma więc postać:

$$K_R = (\rho_p + \beta_p) \mathbf{I}_p + (\rho_G + \beta_G) \mathbf{I}_G + (\rho_{DG} + \beta_{DG}) \mathbf{I}_{DG} + \alpha_p \dot{\mathbf{P}}_n + \alpha_G \dot{\mathbf{G}}_n + \alpha_{DG} \dot{\mathbf{D}}_G + \varepsilon_P \mathbf{P} + \varepsilon_G \mathbf{G} + \varepsilon_{DG} \mathbf{D}_G + \varepsilon_G \mathbf{G} + \mathbf{k}_{DD} \mathbf{D}_D \Rightarrow \min \quad (4.14)$$

gdzie:

K_R - roczny koszt działania podsystemu energetycznego kompleksu budowlanego,

ρ - wektor wierszowy stóp obsługi kapitału inwestycyjnego,

β - wektor wierszowy względnych składników kosztów stałych remontów i konserwacji zależnych od nakładów inwestycyjnych,

$\mathbf{I}$ - wektor kolumnowy nakładów inwestycyjnych,

α - wektor wierszowy wskaźników kosztu płac,

ε - wektor wierszowy wskaźników kosztów eksploatacyjnych; w przypadku dostaw uzupełniających także kosztów zakupy,

$\dot{\mathbf{P}}_n$ - wektor kolumnowy mocy nominalnych urządzeń produkcji podstawowych,

$\dot{\mathbf{G}}_n$ - wektor kolumnowy mocy nominalnych urządzeń produkcji szczytowej,

$\dot{\mathbf{D}}_{Gn}$ - wektor kolumnowy nominalnych strumieni dostaw uzupełniających nośników energii,

$\mathbf{P}$ - wektor kolumnowy rocznej produkcji podstawowej,

$\mathbf{G}$ - wektor kolumnowy rocznej produkcji szczytowej

$\mathbf{D}_G$ - wektor kolumnowy rocznych dostaw uzupełniających,

$\mathbf{k}_{DD}$ - wektor wierszowy kosztów jednostkowych dostaw wyłącznych do podsystemu energetycznego kompleksu budowlanego,

$\mathbf{D}_D$ - wektor kolumnowy dostaw wyłącznych do podsystemu energetycznego.

Indeksy „P”, „G”, „DG”, „DD” dotyczą odpowiednio podstawowej, szczytowej części produkcji, dostaw uzupełniających i dostaw wyłącznych.

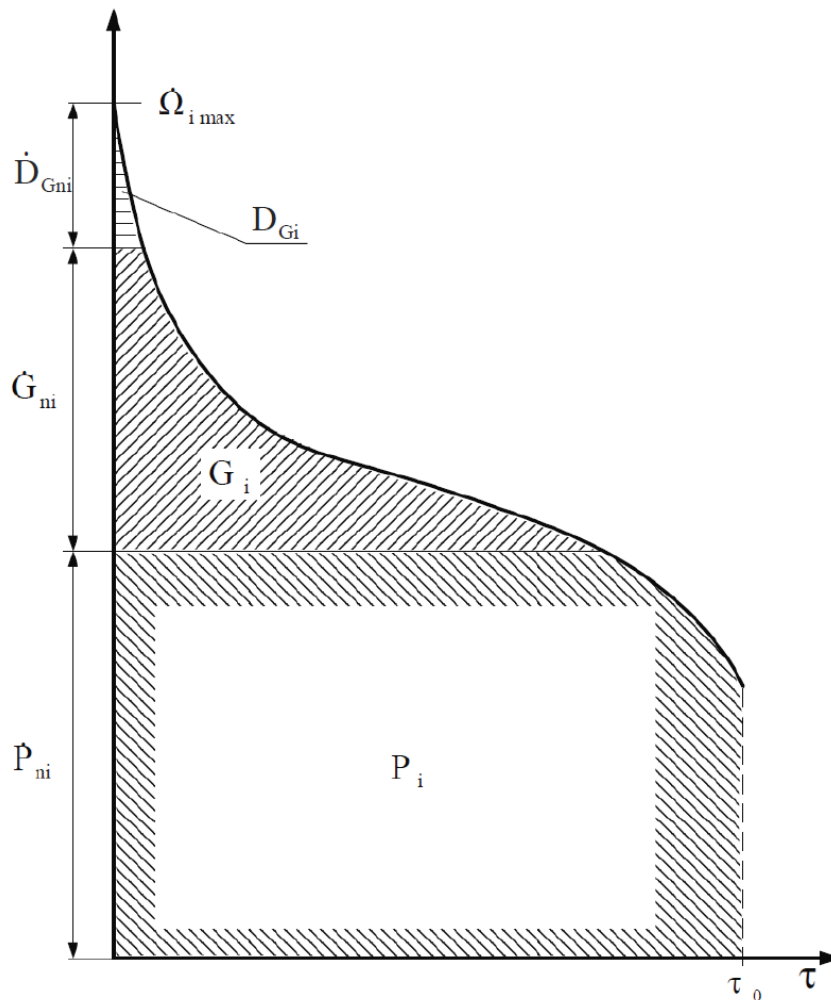
Relacje wiążące roczną produkcję G_i , P_i oraz dostawę uzupełniającą D_G z wartościami mocy nominalnych $\dot{G}_{ni}$, $\dot{P}_{ni}$ oraz strumieni nominalnych dostaw uzupełniających $\dot{D}_{Gni}$ wynikają z równań:

$$G_{ni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{G}_i(\tau) d\tau \quad (4.15)$$

$$P_{ni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{P}_i(\tau) d\tau \quad (4.16)$$

$$D_{Gni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{D}_{Gi}(\tau) d\tau \quad (4.17)$$

gdzie $\dot{G}_i(\tau)$, $\dot{P}_i(\tau)$ i $\dot{D}_{Gi}(\tau)$ oznaczają funkcje opisujące wykresy uporządkowane, a τ_n i τ_0 roczny czas wykorzystania nominalnego obciążenia oraz roczny czas działania urządzeń.



Rys. 4.2. Wykres uporządkowany zapotrzebowania na nośnik energii j-tej gałęzi energetycznej

Zmiennymi decyzyjnymi są wektory mocy i strumieni nominalnych $\dot{\mathbf{G}}_n$, $\dot{\mathbf{P}}_n$, $\dot{\mathbf{D}}_{Gni}$. Wektory produkcji szczytowej $\mathbf{G}$ i podstawowej $\mathbf{P}$, jak również wektor dostaw uzupełniających $\mathbf{D}_G$ są wyznaczone na podstawie dobranych mocy i strumieni nominalnych oraz wykresu uporządkowanego globalnego zapotrzebowania na dany nośnik energii (Rys.4.2). Ograniczenia równościowe stanowi równanie macierzowe bilansu nośników energii stanowiące model opisowy gospodarki energetycznej kompleksu budowlanego. Lokalne ograniczenia dotyczące poszczególnych gałęzi energetycznych wynikają z maksymalnego zapotrzebowania na każdy z nośników energii i z ograniczeń na dostawy zewnętrzne oraz nakłady inwestycyjne, jeżeli takie ograniczenia mają miejsce:

$$\dot{P}_{ni} + \dot{G}_{ni} + \dot{D}_{ni} \leq \dot{\Omega}_{i \max} \quad (4.18)$$

$$\dot{D}_{Gni} \leq \vartheta_{DGi} \text{ oraz } \dot{D}_{Dni} \leq \vartheta_{DDi} \quad (4.19)$$

$$I_{Pi} + I_{Gi} + I_{Di} \leq I_i \quad (4.20)$$

gdzie:

$\dot{\Omega}_{i \max}$ -maksymalne zapotrzebowanie na i-ty nośnik energii,

ϑ_{DGi} - ograniczenie dotyczące dostawy uzupełniającej i-tego nośnika energii,

$\dot{D}_{Dni}$ - nominalny strumień i-ty dostawy wyłącznej do podsystemu energetycznego,

ϑ_{DDi} - ograniczenie i-tej dostawy wyłącznej,

I_i - ograniczenie nakładów inwestycyjnych dotyczące i-tego nośnika energii.

W przypadku dostaw uzupełniających koszty stałe i koszty zmienne, które są brane pod uwagę w analizie dotyczą zmiany parametrów termodynamicznych, transportu i dystrybucji dostawy zewnętrznej. Dostawy wyłączne do kompleksu budowlanego są obciążone jedynie kosztami zakupu.

4.2.3. Dekompozycja globalnego zadania optymalizacyjnego

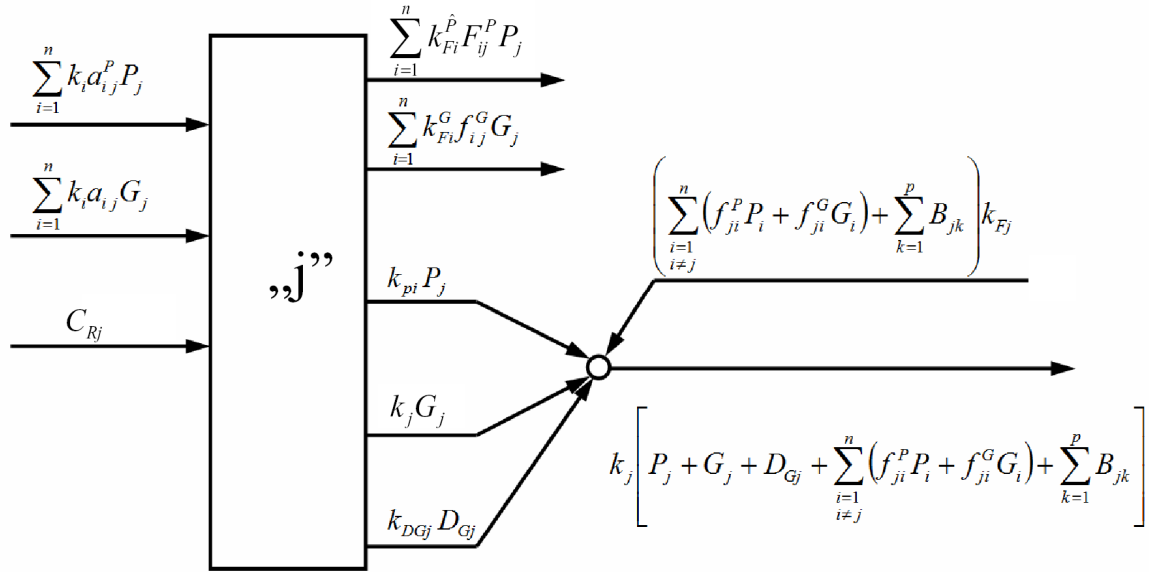
W celu rozwiązania globalnego zadania optymalizacyjnego (4.14) wymagana jest znajomość wykresu uporządkowanego zapotrzebowania na dany nośnik energii, jak również znajomość wskaźników zużycia i ubocznego wytwarzania nośników energii. Te ostatnie określane są na podstawie charakterystyk energetycznych zależnych zarówno od nieznanymi mocy i strumieni nominalnych, jak również od zmiany obciążeń urządzeń i maszyn

energetycznych. Zmiany obciążenia są przedstawione za pomocą wykresów uporządkowanych. Jednak do skonstruowania wykresu uporządkowanego potrzebna jest znajomość wskaźników zużycia lub ubocznego wytwarzania nośników energii. Tak więc, konstrukcja wykresów uporządkowanych zapotrzebowania na nośniki energii, określenie wskaźników jednostkowego zużycia lub ubocznego wytwarzania nośników energii, jak również dobór mocy nominalnych maszyn i urządzeń energetycznych oraz nominalnych strumieni dostaw zewnętrznych są zadaniami wzajemnie ze sobą powiązanymi. Ich rozwiązanie wymaga zastosowania dekompozycji globalnego zadania optymalizacyjnego. W tym celu dostosowana zostanie metoda dekompozycji Lagrange’a. Uwzględniając, że równania bilansu nośników energii dla podsystemu energetycznego kompleksu budowlanego stanowią równania więzów i pomijając wielkości $\mathbf{BI}_v$ i $\mathbf{CI}_v$ (produkcja uboczna i zużycie nośników energii w podsystemie odbiorców kompleksu budowlanego), które nie wpływają na wynik optymalizacji, funkcja celu (4.14) przyjmuje postać:

$$\mathbf{L} = C_R + \lambda(\mathbf{A}_G \mathbf{G} + \mathbf{A}_P \mathbf{P} - \mathbf{G} - \mathbf{P} - \mathbf{F}_G \mathbf{G} - \mathbf{F}_P \mathbf{P} - \mathbf{D}_G) \quad (4.21)$$

gdzie λ jest wektorem wierszowym wskaźników Lagrange’a.

W celu określenia wektora λ wymagana jest znajomość procedury koordynacyjnej zapewniającej zgodność optimum lokalnego wymaganego na poziomie gałęzi energetycznej z optimum globalnym. Dla określenia tej procedury w rozpatrywanej analizie należy sformułować funkcję celu na poziomie j-tej gałęzi energetycznej. Na rys. 4.3. przedstawiono pomocniczy schemat obliczeniowy dla sformułowania gałęziowej funkcji celu i ustalenia dalszych rozważań. Produkcja główna i uboczna stanowią efekty użyteczne działania gałęzi energetycznej. Rozróżnia się koszty jednostkowe wytwarzania produkcji podstawowej i szczytowej oraz produkcji ubocznej danego nośnika energii. Uwzględnia się także dostawę uzupełniającą nośnika energii po koszcie jednostkowym narzuconym przez dostawcę. Dlatego w przypadku zasilania gałęzi energetycznej przez nośnik wytworzony w podsystemie energetycznym kompleksu budowlanego należy posłużyć się średnim kosztem jednostkowym pozyskania danego nośnika energii. Koszty dostaw zewnętrznych (uzupełniających i ubocznych) są ujęte w pozycji K_{Rj} . W przypadku dostaw uzupełniających nakłady obok kosztów zakupu ujmują także koszty stałe i zmienne związane z przygotowaniem dostawy nośnika energii do użytkowania w kompleksie budowlanym (np. koszt eksploatacji węzła ciepłowniczego). Na rys. 4.3. przedstawiono również węzeł sumacyjny dla określenia średniego kosztu nośnika energii.



Rys. 4.3. Pomocniczy schemat dla sformułowania funkcji celu gałęzi energetycznej

Funkcja celu dotycząca j-tej gałęzi podsystemu energetycznego ma postać:

$$\phi = K_{Rj} + \sum_{i=1}^n k_i (a_{ij}^P P_j + a_{ij}^G G_j) - \sum_{i=1}^n k_{Fi} f_{ij}^P P_j - \sum_{i=1}^n k_{Fi} f_{ij}^G G_j \Rightarrow \min \quad (4.22)$$

przy czym

$$K_{Rj} = (\rho_{Pj} + \beta_{Pj}) I_{Pj} + (\rho_{Gj} + \beta_{Gj}) I_{Gj} + (\rho_{DGj} + \beta_{DGj}) I_{DGj} + \alpha_{Pj} \dot{P}_{nj} + \alpha_{Gj} \dot{G}_{nj} + \alpha_{DGj} \dot{D}_{Gj} + \varepsilon_{Pj} G_j + \varepsilon_{Gj} P_j + \varepsilon_{DGj} D_{Gj} + \sum_{l=n+1}^m k_{DDl} a_{lj}^{PD} P_j + \sum_{l=n+1}^m k_{DDl} a_{lj}^{GD} G_j \quad (4.23)$$

gdzie:

K_{Rj} - część funkcji (9.1) dotycząca j-tej gałęzi energetycznej,

k_i - średnioważony koszt jednostkowy j-tego nośnika energii,

k_{Pj} - koszt jednostkowy podstawowej części produkcji głównej,

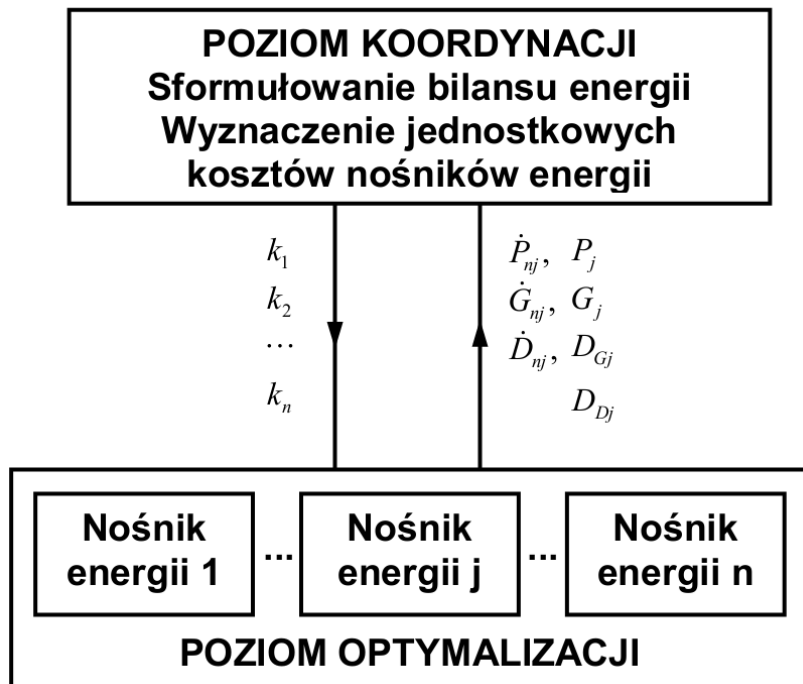
k_{Fj}, k_{Fi} - koszty jednostkowe produkcji ubocznej j-tej oraz i-tej gałęzi,

k_{Gj} - koszt jednostkowy szczytowej części produkcji głównej,

k_{DDl} - koszt jednostkowy dostawy wyłącznej nośnika energii.

Indeksy „i” oraz „j” dotyczą zamiennie gałęzi energetycznych podsystemu energetycznego kompleksu budowlanego.

Zastosowanie metody dekompozycji sprowadza zadanie optymalizacyjne do procedury iteracyjnej. W kolejnym kroku iteracyjnym na górnym poziomie hierarchii jest określony za pomocą procedury koordynacyjnej wektor mnożników Lagrange’a, który jest następnie przesyłany na dolny poziom hierarchii. Jest to podstawa do autonomicznej optymalizacji każdej z gałęzi energetycznych. W rozpatrywanym przypadku na dolnym poziomie hierarchii są wyznaczane optymalne wartości mocy znamionowych maszyn i urządzeń energetycznych oraz nominalna wartość strumieni dostaw uzupełniających i wyłącznych nośników energii (rys. 4.4).



Rys. 4.4. Schemat dekompozycji za pomocą metody Lagrange’a

W równaniu (4.22) dotyczącym funkcji celu na poziomie optymalizacji rozpatrywanej gałęzi koszty jednostkowe k_i oraz k_{Fj} nośników energii są zadane. Następujące człony funkcji celu mogą być także przyjęte jako wielkości stałe:

$$k_j (P_j + G_j + D_{Gj}) = \text{const} \quad (4.24)$$

$$(k_j - k_{Fj}) \sum_{i=1}^n (f_{ij}^P P_i + f_{ij}^G G_i) = \text{const} \quad (4.25)$$

Człon (4.24) ma wielkość stałą, ponieważ w kolejnej iteracji globalne zapotrzebowanie na j-ty nośnik energii jest zadane, optymalizacja zaś dotyczy rozdziału pokrycia zapotrzebowania pomiędzy produkcją własną (szczytową i uboczną) oraz dostawę uzupełniającą nośnika energii z zewnątrz. Człon (4.25) przyjmuje również wartość stałą w

kolejnej iteracji, ponieważ sumowanie dotyczy indeksów „i” z wyjątkiem $i=j$. Dlatego człony (4.24) i (4.25) mogą być wprowadzone do funkcji celu (4.22) bez wpływu na rezultat optymalizacji.

Po zsumowaniu funkcji celu (4.22) dla wszystkich gałęzi energetycznych rozpatrywanych na poziomie optymalizacji z dodatkowo wprowadzonymi członami (4.24) i (4.25) otrzymuje się:

$$\begin{aligned} \sum_{j=1}^n \phi_j = & \sum_{j=1}^n K_{Rj} + \sum_{j=1}^n \sum_{i=1}^n k_i (a_{ij}^P P_j + a_{ij}^G G_j) - \sum_{j=1}^n \sum_{i=1}^n k_{Fi} f_{ij}^P P_j - \sum_{j=1}^n \sum_{i=1}^n k_{Fi} f_{ij}^G G_j - \\ & - \sum_{j=1}^n k_j (P_j + G_j + D_{Gj}) - \sum_{j=1}^n k_j \sum_{i=1}^n (f_{ij}^P P_i + f_{ji}^G G_j) + \sum_{j=1}^n k_{Fi} \sum_{i=1}^n f_{ij}^P P_i + \sum_{j=1}^n k_{Fj} \sum_{i=1}^n f_{ji}^G G_j \end{aligned} \quad (4.26)$$

Upraszczając wyrazy podobne w równaniu (1.13) i stosując zapis macierzowy otrzymuje się:

$$\sum_{j=1}^n \phi_j = K_R + \mathbf{k}^T (\mathbf{A}_G \mathbf{G} + \mathbf{A}_P \mathbf{P} - \mathbf{G} - \mathbf{P} - \mathbf{F}^G \mathbf{G} - \mathbf{F}^P \mathbf{P} - \mathbf{D}_G) \quad (4.27)$$

gdzie $\mathbf{k}$ oznacza wektor kolumnowy średnioważonych kosztów jednostkowych nośników energii.

Porównując równania (4.27) i (4.21) można napisać:

$$L = \sum_{j=1}^n \phi_j \quad (4.28)$$

i

$$\lambda = \mathbf{k}^T \quad (4.29)$$

Tak więc, mnożniki Lagrange’a odpowiadają średnioważonym jednostkowym kosztom nośnika energii w podsystemie energetycznym kompleksu budowlanego. Dlatego metoda macierzowa obliczania kosztów jednostkowych nośników energii stanowi procedurę koordynacyjną w zdekomponowanym modelu optymalizacyjnym doboru struktury podsystemu energetycznego kompleksu budowlanego.

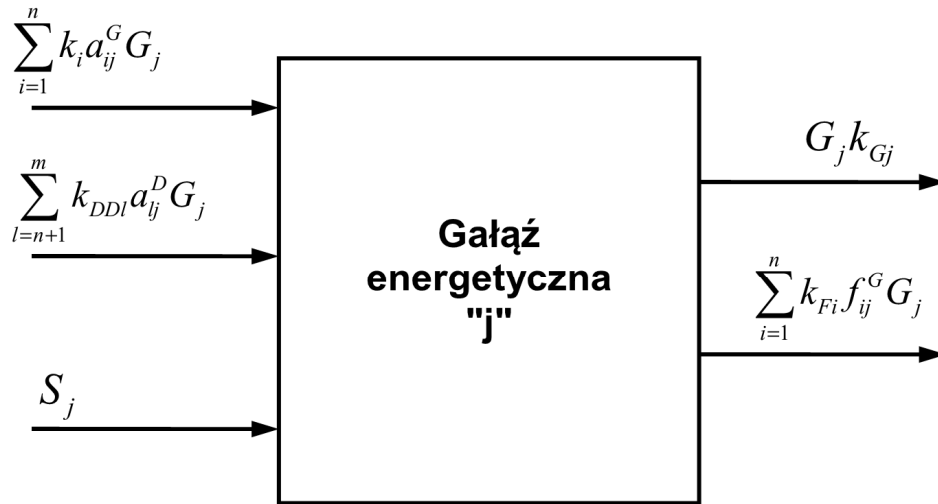
W pierwszym przybliżeniu iteracyjnego algorytmu dekompozycji wektory $\mathbf{k}$ i $\mathbf{k}_F$ kosztów jednostkowych są zakładane. Zakładane są również te wskaźniki jednostkowego zużycia nośników energii, które mają charakter sprzężeń zwrotnych (tzn. znajdują się poniżej głównej przekątnej macierzy „input-output” powiązań międzygałęziowych). Po rozwiązaniu autonomicznych zadań optymalizacyjnych z uwzględnieniem lokalnych ograniczeń dla wszystkich gałęzi na niższym poziomie hierarchii następuje powrót na górny poziom hierarchii (poziom koordynacji), gdzie sporządzany jest skorygowany bilans energii

i wyznaczany nowy wektor kosztów jednostkowych nośników energii według procedury koordynacyjnej. Skorygowany wektor kosztów jest przekazywany na dolny poziom hierarchii, gdzie następuje autonomiczna optymalizacja poszczególnych gałęzi energetycznych w kolejnej iteracji. Koniec iteracji wynika z założonej dokładności obliczeń kosztów jednostkowych nośników energii.

4.2.4. Metoda macierzowa obliczania kosztów jednostkowych nośników energii

Złożoność powiązań w gospodarce energetycznej, z których część ma charakter sprzężeń zwrotnych powoduje, że koszty jednostkowe nośników energii można wyznaczyć jedynie drogą kolejnych przybliżeń. Tak np. w celu wyznaczenia kosztu jednostkowego energii elektrycznej konieczna jest znajomość kosztu czynnika napędowego (pary świeżej w przypadku turbiny parowej lub spalin w przypadku turbiny gazowej), który z kolei zależy od poszukiwanego kosztu energii elektrycznej. Dlatego zastosowanie metody macierzowej obliczania kosztów jednostkowych nośników energii bazującej na modelu „input-output” bilansu energetycznego prowadzi do rozwiązania problemu. Warunkiem koniecznym zastosowania metody macierzowej obliczania kosztów jednostkowych nośników energii jest zamknięty bilans energii według wspomnianego modelu „input-output”.

Nośniki energii zużywane w kompleksie budowlanym mogą być wytwarzane jako produkty główne lub uboczne w podsystemie energetycznym lub mogą być dostarczane z zewnątrz. Dlatego rozróżnia się koszty jednostkowe podstawowej i szczytowej części produkcji głównej, koszty produkcji ubocznej i uzupełniających dostaw zewnętrznych. W przypadku zużycia nośników energii należy posłużyć się średnioważonym kosztem jednostkowym uwzględniając dodatkowo koszty zmiany parametrów, transportu i dystrybucji.



Rys. 4.5. Bilans kosztów w przypadku produkcji szczytowej gałęzi „j”

Bilans kosztów dotyczący szczytowej części produkcji j-tej gałęzi energetycznej (Rys. 4.5) ma postać:

$$\sum_{i=1}^n k_i a_{ij}^G G_j + \sum_{l=n+1}^m k_{DDl} a_{lj}^{GD} G_j + S_j = G_j k_{Gj} + \sum_{i=1}^n k_{Fi} f_{ij}^G G_j \quad (4.30)$$

gdzie:

k_i – średnioważony koszt jednostkowy i-tego nośnika energii,

k_{DDl} – koszt jednostkowy l-tej dostawy wyłącznej,

k_{Gj} – koszt jednostkowy szczytowej części produkcji j-tego nośnika energii,

k_{Fi} – koszt jednostkowy i-tego nośnika energii produkowanego ubocznie,

S_j – umowny koszt stały.

Człon S_j obejmuje wszystkie pozostałe składniki kosztu poza kosztami zużywanych nośników energii. Z uwagi na to, że S_j zawiera głównie koszty stałe, został on nazwany umownym kosztem stałym.

Średnioważony koszt jednostkowy k_i dotyczący i-tego nośnika energii jest obliczany z równania:

$$k_i = r_{Pi} k_{Pi} + r_{Gi} k_{Gi} + r_{Fi} k_{Fi} + r_{DGi} k_{DGi} \quad (4.31)$$

gdzie:

$r_{Pi}, r_{Gi}, r_{Fi}, r_{DGi}$ - udziały produkcji podstawowej, szczytowej, ubocznej i dostaw uzupełniających w globalnym przychodzie i-tego nośnika energii,

$k_{Pi}, k_{Gi}, k_{Fi}, k_{DGi}$ - koszty jednostkowej produkcji podstawowej, szczytowej oraz ubocznej i dostaw uzupełniających.

Układ równań bilansowych kosztów szczytowej części produkcji głównej przyjmuje w zapisie macierzowym postać:

$$(\mathbf{A}_G \mathbf{G}^d)^T \mathbf{k} + (\mathbf{A}_{GD} \mathbf{G}^d)^T \mathbf{k}_{DD} + \mathbf{S}_G = \mathbf{G}^d \mathbf{k}_G + (\mathbf{F}_G \mathbf{G}^d)^T \mathbf{k}_F \quad (4.32)$$

gdzie “d” oznacza operację tworzenia macierzy diagonalnych z wektora kolumnowego.

Podobnie układ równań bilansowych podstawowej części produkcji można przedstawić jak niżej:

$$(\mathbf{A}_P \mathbf{P}^d)^T \mathbf{k} + (\mathbf{A}_{PD} \mathbf{P}^d)^T \mathbf{k}_{DD} + \mathbf{S}_P = \mathbf{P}^d \mathbf{k}_P + (\mathbf{F}_P \mathbf{P}^d)^T \mathbf{k}_F \quad (4.33)$$

gdzie w równaniach (4.32)÷(4.33) oznaczają:

$\mathbf{k}$ - wektor średnioważonych kosztów jednostkowych nośników energii,

$\mathbf{k}_P$ - wektor kosztów jednostkowych podstawowej części produkcji głównej,

$\mathbf{k}_G$ - wektor kosztów jednostkowych szczytowej części produkcji głównej,

$\mathbf{k}_F$ - wektor kosztów jednostkowych produkcji ubocznej,

$\mathbf{k}_{DG}$ - wektor kosztów jednostkowych dostaw uzupełniających,

$\mathbf{k}_{DD}$ - wektor kosztów jednostkowych dostaw wyłącznych,

$\mathbf{r}_P^d$ - macierz diagonalna udziałów produkcji podstawowej,

$\mathbf{r}_G^d$ - macierz diagonalna udziałów produkcji szczytowej,

$\mathbf{r}_F^d$ - macierz diagonalna udziałów produkcji ubocznej,

$\mathbf{r}_{DG}^d$ - macierz diagonalna udziałów dostaw uzupełniających.

Równania (4.32) ÷ (4.33) stanowią algorytm metody macierzowej obliczania kosztów jednostkowych nośników energii. Koszty jednostkowe produktów ubocznych są określone na podstawie metody kosztów unikniętych. Koszty jednostkowe dostaw zewnętrznych (uzupełniających i wyłącznych) są wielkościami zadanymi (ceny nośników energii obowiązujące w krajowym systemie energetycznym).

5. Przykład obliczeniowy doboru struktury gospodarki energetycznej kompleksu budowlanego

5.1. Scenariusz gospodarki energetycznej analizowanego kompleksu budowlanego

W gospodarce energetycznej przykładowego kompleksu budowlanego zaproponowano wykorzystanie małego układu skojarzonego bazującego na tłokowym silniku spalinowym, mikroturbinie gazowej lub ogniwie paliwowym. Postanowiono rozpatrzyć warianty gospodarki energetycznej budynku przy spełnieniu warunku, że poszczególnym wariantom jest przypisana jedna technologia skojarzonego wytwarzania ciepła i elektryczności. W tym celu zastosowano kryterium zgodności technologii. Rozważono także wykorzystanie gospodarki elektryczno-cieplno-chłodniczej (trigeneration) poprzez wykorzystanie ciepła z układu skojarzonego w chłodziarce absorpcyjnej zasilanej gorącą wodą. Dopuszczono możliwość dostawy z zewnątrz energii elektrycznej i ciepła oraz wytwarzania chłodu w sprężarkowym agregacie chłodniczym. Podsystem odbiorców w analizowanym budynku wymaga pokrycia zapotrzebowania na gorącą wodę procesową na dwóch poziomach temperaturowych oraz na ciepłą wodę użytkową. Woda procesowa zasila instalację ogrzewania oraz nagrzewnicę w centrali klimatyzacyjnej. Przewidziano trzy czynniki chłodnicze o różnych temperaturach, które zapewniają odbiór ciepła z systemu klimatyzacji, chłodni oraz pomieszczeń magazynowych. Dopuszczono możliwość produkcji chłodu w chłodziarce absorpcyjnej zasilanej gazem ziemnym. Przewidziano również zainstalowanie urządzeń szczytowych, a mianowicie kotła wodnego zasilanego gazem ziemnym bądź olejem opałowym oraz sprężarkowego agregatu chłodniczego zasilanego energią elektryczną.

W tablicy 5.1 przedstawiono uniwersalną listę nośników energii dla rozważanego budynku. Oprócz nośników energii zużywanych przez podsystem technologiczny (które ujmuje wektor binarny $\mathbf{O}^b$) na uniwersalnej liście znajdują się nośniki energii, których produkcja wynika z powiązań międzygałęziowych w podsystemie energetycznym. Wyróżniono 10 nośników energii wytwarzanych jako produkty główne ujęte za pomocą wektora binarnego $\mathbf{B}_G^b$ oraz 4 nośniki sprowadzane z zewnątrz do budynku jako dostawy wyłączone, które ujmuje wektor $\mathbf{B}_D^b$.

Tablica 5.1. Uniwersalna lista nośników energii , wektor B_G^b charakteryzujący nośniki energii wytwarzane jako produkty główne, wektor B_D^b dotyczący dostaw zewnętrznych wyłącznych oraz wektor O^b zapotrzebowania nośników energii przez podsystem odbiorców

i	Nośnik energii	B_G^b	B_D^b	O^b
1	Energia elektryczna	1	0	1
2	Ciepło grzejne	1	0	0
3	Chłód	1	0	0
4	Woda gorąca zasilająca chłodziarkę absorpcyjną I	1	0	0
5	Czynnik chłodzący 6/12°C	1	0	1
6	Gorąca woda procesowa I 60/45°C	1	0	1
7	Gorąca woda procesowa II 85/55°C	1	0	1
8	Ciepła woda użytkowa	1	0	1
9	Powietrze z centrali klimatyzacyjnej	1	0	1
10	Powietrze wentylacyjne	1	0	1
11	Woda wodociągowa	0	1	1
12	Gaz ziemny	0	1	1
13	Olej opałowy	0	1	0
14	Olej napędowy	0	1	0

5.2. Opracowanie zbioru dopuszczalnych wariantów gospodarki energetycznej analizowanego kompleksu budowlanego

Na podstawie scenariusza gospodarki energetycznej tworzy się zbiór tematów projektowych i rozwiązań technicznych, które w dalszej kolejności są podstawą do utworzenia zbioru wszystkich możliwych do zrealizowania wariantów gospodarki energetycznej kompleksu budowlanego. Zbiór ten podlega następnie weryfikacji z punktu widzenia kryterium zgodności technologii i eliminacji zbędnych rozwiązań.

W celu wytworzenia nośników energii na potrzeby podsystemu odbiorców niezbędny jest określony zbiór urządzeń energetycznych podsystemu energetycznego. Zbiór ten zawiera technicznie dostępne i ekonomicznie uzasadnione urządzenia energetyczne dobrane na podstawie zapotrzebowania podsystemu odbiorców na nośniki energii. W tablicy 5.2 przedstawiono zbiór urządzeń energetycznych możliwych do zainstalowania w przykładowym budynku.

Tablica 5.2. Tablica urządzeń energetycznych rozważanych do zainstalowania w analizowanym kompleksie budowlanym

	Urządzenie energetyczne

U1	Sprężarkowy agregat chłodniczy
U2	Chłodziarka absorpcyjna I – zasilana gorącą wodą
U3	Chłodziarka absorpcyjna II –zasilana gazem ziemnym
U4	Kotły wodne opalane olejem opałowym
U5	Kotły wodne opalane gazem ziemnym
U6	Układ CHP z tłokowym silnikiem spalinowym zasilanym olejem napędowym
U7	Układ CHP z mikroturbiną gazową zasilaną gazem ziemnym
U8	Układ CHP z ogniwem paliwowym zasilanym gazem ziemnym
U9	Szczytowy kocioł gazowy
U10	Szczytowy kocioł olejowy
U11	Szczytowy, sprężarkowy agregat chłodniczy
U12	Centrala klimatyzacyjna
U13	System wentylacji wyciągowej
U14	Wymiennik chłodu –czynnik chłodzący 6/12°C
U15	Wymiennik ciepła I –gorąca woda 60/45°C
U16	Wymiennik ciepła II –gorąca woda 85/55°C
U17	Wymiennik CWU

Zbiór tematów projektowych i rozwiązań technicznych został przedstawiony w formie binarnej macierzy tematów projektowych **II** (tablica 5.3). W macierzy ujęto wszystkie tematy projektowe oraz rozwiązania techniczne przewidziane do realizacji w przykładowym budynku. Wyróżniono 14 tematów projektowych i 31 odpowiadających im rozwiązań technicznych. Poszczególne wiersze macierzy **II** (tablica 5.3) odpowiadają rozwiązaniom technicznym, a kolumny określonym urządzeniom energetycznym w przykładowym kompleksie budowlanym. Ostatnia kolumna ujmuje dostawy nośników energii z zewnątrz. Przykładowo temat projektowy nr 1 obejmujący 4 rozwiązania techniczne dotyczy wytwarzania bądź dostawy energii elektrycznej. Rozwiązanie techniczne nr 1 (pierwszy wiersz tablicy 5.3) polega na wyłącznej dostawie energii elektrycznej z zewnątrz. Następne trzy rozwiązania techniczne obejmują wykorzystanie kolejno układu CHP z tłokowym silnikiem spalinowym zasilanym olejem napędowym, układu CHP z mikroturbiną gazową zasilaną gazem ziemnym oraz układu CHP z ogniwem paliwowym (U6, U7, U8 – tablica 5.2 i 5.3) wraz z dostawą uzupełniającą energii elektrycznej z sieci elektroenergetycznej.

Tablica 5.3. Macierz binarna tematów projektowych i rozwiązań technicznych II

Temat projektowy	Nr rozw. tech.	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	DOSTAWA
1 Energia elektryczna	1						1												1
	2							1											1
	3							1											1
	4								1										1
2 Ciepło	5																		1
	6				1					1									
	7					1				1									
	8				1						1								
	9					1					1								
	10						1				1								
	11						1				1								
	12							1			1								
	13							1			1								
	14								1	1									
	15								1		1								
3 Chłód	16	1										1							
	17		1									1							
	18			1								1							
4 Woda zasilająca ziębiarkę 1	19						1												
	20							1											
	21								1										
5 Czynnik chł. 6/12 C	22														1				
6 Woda gorąca 60/45 C	23															1			
7 Woda gorąca 2 85/55 C	24																1		
8 CWU	25																	1	
9 Powietrze z centrali klimatyzacyjnej	26												1						
10 Powietrze wentylacyjne	27													1					
11 Woda wodociągowa	28																		1
12 Gaz ziemny	29																		1
13 Olej opałowy	30																		1
14 Olej napędowy	31																		1

Tablica 5.4. Macierz binarna Z^b

Nośnik en./Rozwiązanie techniczne	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1 Energia elektryczna	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
2 Ciepło	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0
3 Chłód	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
4 Woda zasilająca ziębiarkę 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5 Czynnik chł. 6/12 C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6 Woda gorąca 60/45 C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7 Woda gorąca 2 85/55 C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8 CWU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9 Powietrze z centrali klimatyzacyjnej	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10 Powietrze wentylacyjne	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 Woda wodociągowa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
12 Gaz ziemny	0	0	1	1	0	1	1	0	1	1	0	1	1	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
13 Olej opałowy	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14 Olej napędowy	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Tablica 5.5. Zbiór wariantów gospodarki energetycznej kompleksu budowlanego po procesie eliminacji –wektory W_l^b

Temat projektowy	Nr. rozw. tech.	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25	W26	W27	W28
Energia elektryczna	1	1	1																			1	1	1	1	1	1	1	1
	2			1	1	1	1	1	1																				1
	3									1	1	1	1	1	1														
	4															1	1	1	1	1	1	1							
Ciepło	5	1	1																										
	6																					1				1			
	7																						1				1		
	8																							1				1	
	9																								1				1
	10			1	1	1																							
	11						1	1	1																				1
	12									1	1	1																	
	13												1	1	1														
	14															1	1	1											
	15																		1	1	1	1							
Chłód	16	1		1			1			1			1			1			1	1	1		1	1	1	1			
	17				1			1			1			1			1			1							1	1	1
	18		1			1			1			1			1			1			1					1	1	1	1
Woda zasilająca ziębiarkę 1	19				1			1													1						1	1	1
	20										1			1															1
	21															1				1									
Czynnik chl. 6/12 C	22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Woda gorąca 60/45 C	23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Woda gorąca 85/55 C	24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CWU	25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Powietrze z centrali klimatyzacyjnej	26	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Powietrze wentylacyjne	27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Woda wodociągowa	28	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Gaz ziemny	29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Olej opałowy	30	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	1	0	1	1	1	0	1	1
Olej napędowy	31	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Tablica 5.6. Struktura zużycia nośników energii w poszczególnych wariantach gospodarki energetycznej kompleksu budowlanego – wektory X_l^b

Nośnik en./Nr wariantu	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22	X23	X24	X25	X26	X27	X28
1 Energia elektryczna	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2 Ciepło	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3 Chłód	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4 Woda zasilająca ziębiarkę 1	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
5 Czynnik chl. 6/12 C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6 Woda gorąca 60/45 C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7 Woda gorąca 85/55 C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8 CWU	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9 Powietrze z centrali klimatyzacyjnej	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10 Powietrze wentylacyjne	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11 Woda wodociągowa	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12 Gaz ziemny	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13 Olej opałowy	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	1	0	1	1	1	0	1	1
14 Olej napędowy	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Tablica 5.7. Binarna macierz powiązań międzygałęziowych $A_p^b + F_p^b$ dla wariantu 4 gospodarki energetycznej przykładowego kompleksu budowlanego

Nośnik en./Nr tematu proj.	1	2	3	4	5	6	7	8	9	10
1 Energia elektryczna	1	1	1	1	1	1	1	1	1	1
2 Ciepło	0	0	0	0	0	1	1	1	0	0
3 Chłód	0	0	0	0	1	0	0	0	0	0
4 Woda zasilająca ziębiarkę 1	0	0	1	0	0	0	0	0	0	0
5 Czynnik chł. 6/12 C	0	0	0	0	0	0	0	0	1	0
6 Woda gorąca 60/45 C	0	0	0	0	0	0	0	0	0	0
7 Woda gorąca 85/55 C	0	0	0	0	0	0	0	0	1	0
8 CWU	0	0	0	0	0	0	0	0	0	0
9 Powietrze z centrali klimatyzacyjnej	0	0	0	0	0	0	0	0	0	0
10 Powietrze wentylacyjne	0	0	0	0	0	0	0	0	0	0
11 Woda wodociągowa	0	0	0	0	0	0	0	1	0	0
12 Gaz ziemny	0	1	0	0	0	0	0	0	0	0
13 Olej opałowy	0	0	0	0	0	0	0	0	0	0
14 Olej napędowy	1	1	0	1	0	0	0	0	0	0

Tablica 5.8. Binarna macierz powiązań międzygałęziowych $A_p^b + F_p^b$ dla wariantu 11 gospodarki energetycznej przykładowego kompleksu budowlanego

Nośnik en./Nr tematu proj.	1	2	3	4	5	6	7	8	9	10
1 Energia elektryczna	1	1	1	0	1	1	1	1	1	1
2 Ciepło	0	0	0	0	0	1	1	1	0	0
3 Chłód	0	0	0	0	1	0	0	0	0	0
4 Woda zasilająca ziębiarkę 1	0	0	0	0	0	0	0	0	0	0
5 Czynnik chł. 6/12 C	0	0	0	0	0	0	0	0	1	0
6 Woda gorąca 60/45 C	0	0	0	0	0	0	0	0	0	0
7 Woda gorąca 85/55 C	0	0	0	0	0	0	0	0	1	0
8 CWU	0	0	0	0	0	0	0	0	0	0
9 Powietrze z centrali klimatyzacyjnej	0	0	0	0	0	0	0	0	0	0
10 Powietrze wentylacyjne	0	0	0	0	0	0	0	0	0	0
11 Woda wodociągowa	0	0	0	0	0	0	0	1	0	0
12 Gaz ziemny	1	1	1	0	0	0	0	0	0	0
13 Olej opałowy	0	0	0	0	0	0	0	0	0	0
14 Olej napędowy	0	0	0	0	0	0	0	0	0	0

Tablica 5.9. Binarna macierz powiązań międzygałęziowych $A_p^b + F_p^b$ dla wariantu 28 gospodarki energetycznej przykładowego kompleksu budowlanego

Nośnik en./Nr tematu proj.	1	2	3	4	5	6	7	8	9	10
1 Energia elektryczna	0	1	1	0	1	1	1	1	1	1
2 Ciepło	0	0	0	0	0	1	1	1	0	0
3 Chłód	0	0	0	0	1	0	0	0	0	0
4 Woda zasilająca ziębiarkę 1	0	0	1	0	0	0	0	0	0	0
5 Czynnik chł. 6/12 C	0	0	0	0	0	0	0	0	1	0
6 Woda gorąca 60/45 C	0	0	0	0	0	0	0	0	0	0
7 Woda gorąca 85/55 C	0	0	0	0	0	0	0	0	1	0
8 CWU	0	0	0	0	0	0	0	0	0	0
9 Powietrze z centrali klimatyzacyjnej	0	0	0	0	0	0	0	0	0	0
10 Powietrze wentylacyjne	0	0	0	0	0	0	0	0	0	0
11 Woda wodociągowa	0	0	0	0	0	0	0	1	0	0
12 Gaz ziemny	0	1	0	0	0	0	0	0	0	0
13 Olej opałowy	0	1	0	0	0	0	0	0	0	0
14 Olej napędowy	0	0	0	0	0	0	0	0	0	0

Każde z 31 rozwiązań technicznych zostało opisane za pomocą binarnych macierzy powiązań $A_p^b, A_p^b, F_p^b, F_p^b$. Na podstawie macierzy powiązań w poszczególnych rozwiązaniach technicznych utworzono macierz binarną Z^b . Macierz ta została przedstawiona w tablicy 5.4. Ujmuje ona strukturę zużycia nośników energii w poszczególnych rozwiązaniach technicznych. Przykładowo rozwiązanie techniczne nr 2 obejmujące wytwarzanie energii elektrycznej w układzie CHP z tłokowym silnikiem spalinowym (druga kolumna w tablicy 5.4) wiąże się ze zużyciem energii elektrycznej oraz

oleju napędowego (wiersz 1 i 14 macierzy $\mathbf{Z}^b$). W przypadku analizowanego budynku dostawa nośników energii nie jest związana ze zużyciem innych nośników, dlatego kolumna 1 oraz kolumny 28-31 macierzy $\mathbf{Z}^b$ zawierają wyłącznie elementy zerowe.

Wybierając po jednym rozwiązaniu technicznym z każdego tematu projektowego stworzono zbiór wszystkich możliwych do zrealizowania wariantów struktury gospodarki energetycznej w przykładowym budynku. W tym celu zastosowano metodę przeglądu zupełnego grafu. Liczba wszystkich możliwych wariantów gospodarki energetycznej wynosi dla analizowanego przypadku $N=396$ (równanie 6.4), jednak znaczna ich część nie nadaje się do dalszych rozważań z uwagi na brak ekonomicznego uzasadnienia ich realizacji. Ze zbioru wszystkich możliwych wariantów gospodarki energetycznej, określonego na podstawie przeglądu zupełnego grafu, wykluczono warianty nie spełniające kryterium zgodności technologii. Pozostała część wariantów została przeanalizowana pod względem eliminacji zbędnych rozwiązań technicznych tak jak przedstawiono to w punkcie 4.

W tablicy 5.10 przedstawiono wektor $\mathbf{W}_1^b$ przed eliminacją. Tablica 5.11 ujmuje wektor $\mathbf{X}_1^b$, który zawiera jeden element zerowy oznaczający brak zapotrzebowania w wariantcie 4 na olej opałowy. Dlatego rozwiązanie nr 30 dotyczące dostarczania oleju opałowego do budynku zostało wykluczone z wariantu 4 (element nr 30 wektora $\mathbf{W}_1^b$ jest zerowy –tablica 5.5). W tablicy 5.6 zebrano wektory $\mathbf{X}_1^b$ dla wszystkich rozpatrywanych wariantów.

Powstała w ten sposób baza obejmująca 28 wariantów gospodarki energetycznej przykładowego budynku została przedstawiona w tablicy 5.5 w formie wektorów $\mathbf{W}_1^b$. W tablicy 5.5 przedstawiono również przykład wykluczonego wariantu. Wariant ten nie został wzięty do dalszych rozważań, gdyż poprzez jednoczesne zastosowanie modułu skojarzonego opartego na tłokowym silniku spalinowym i ogniwie paliwowym do produkcji ciepła i elektryczności nie spełnia on kryterium zgodności technologii.

Na podstawie znajomości macierzy binarnych $\mathbf{A}_{pP}^b, \mathbf{A}_{pG}^b, \mathbf{F}_{pP}^b, \mathbf{F}_{pG}^b$ oraz równań (6.5)-(6.13) określono dla każdego z wariantów binarną macierz powiązań międzygałęziowych $\mathbf{A}_p^b + \mathbf{F}_p^b$. Macierz powiązań dla wariantu 4 przedstawia tablica 5.6. Wariant ten przewiduje realizację gospodarki skojarzonej ciepłno-elektrycznej w układzie CHP z tłokowym silnikiem spalinowym.

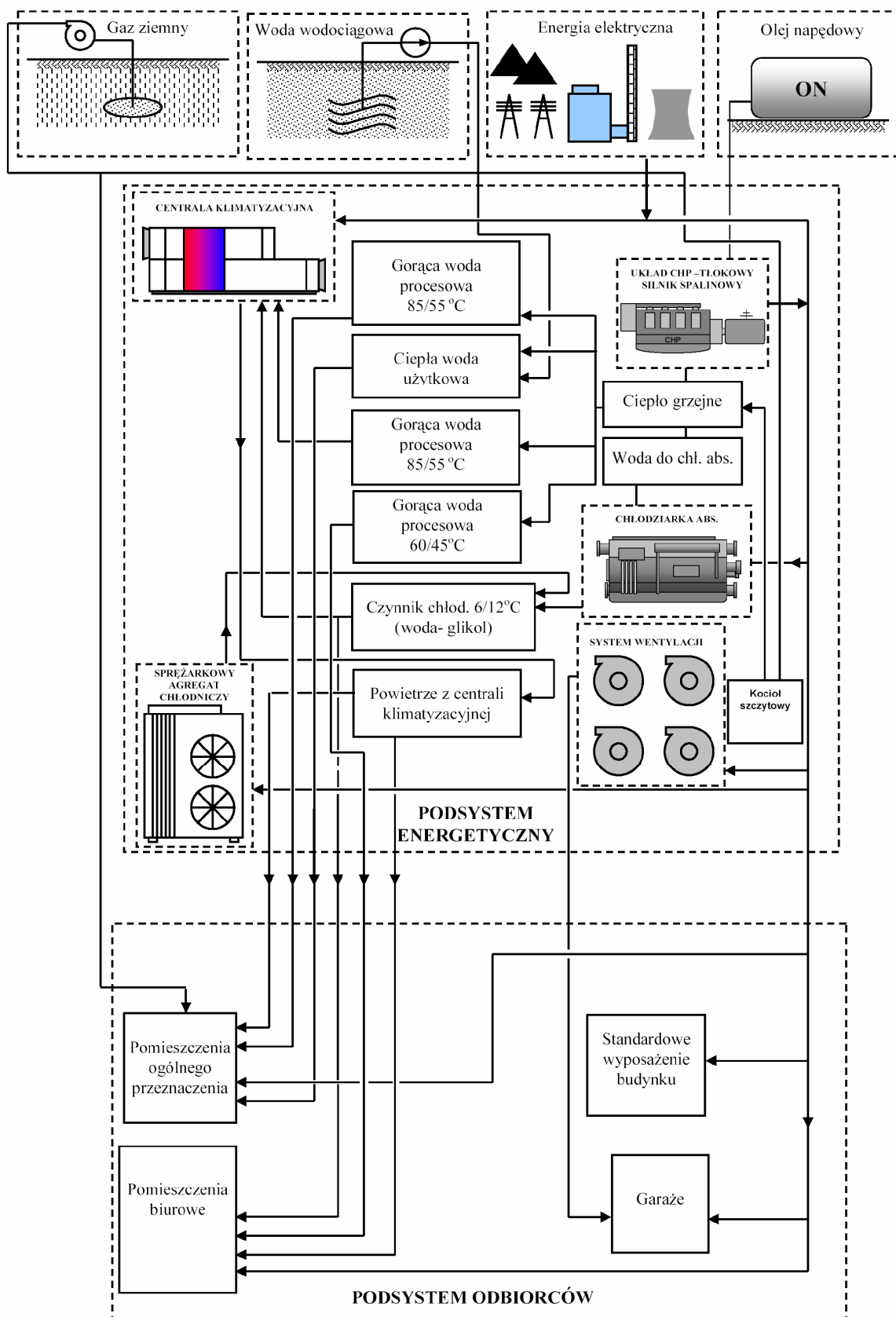
Tablica 5.10 Wektor W_4^b przed eliminacją zbędnego rozwiązania technicznego (wariant 4)

Nr rozw. tech.	W4
1	0
2	1
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	1
11	0
12	0
13	0
14	0
15	0
16	0
17	1
18	0
19	1
20	0
21	0
22	1
23	1
24	1
25	1
26	1
27	1
28	1
29	1
30	1
31	1

Tablica 5.11 Wektor X_4^b określający zapotrzebowanie na nośniki energii w danym wariantcie (wariant 4)

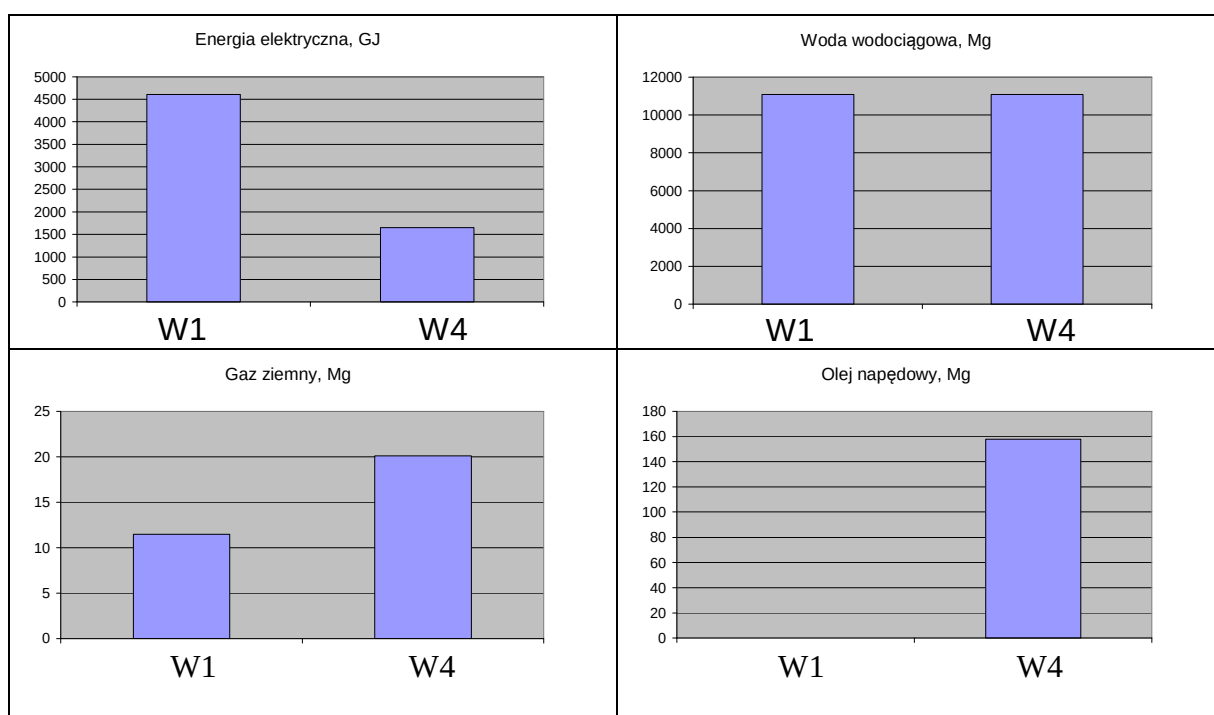
	Nośnik energii	X4
1	Energia elektryczna	1
2	Ciepło	1
3	Chłód	1
4	Woda zasilająca ziębiarkę 1	1
5	Czynnik chł. 6/12 C	1
6	Woda gorąca 60/45 C	1
7	Woda gorąca 2 85/55 C	1
8	CWU	1
9	Powietrze z centrali klimatyzacyjnej	1
10	Powietrze wentylacyjne	1
11	Woda wodociągowa	1
12	Gaz ziemny	1
13	Olej opałowy	0
14	Olej napędowy	1

Układ CHP produkuje oprócz elektryczności i ciepła również gorącą wodę zasilającą chłodziarkę absorpcyjną. W okresie szczytu ciepło produkowane jest w gazowym kotle szczytowym a chłód w szczytowym sprężarkowym agregacie chłodniczym. Schemat tak zmodyfikowanej gospodarki energetycznej analizowanego kompleksu budowlanego przedstawiono na rys. 5.1. Tablice 5.7 i 5.8 przedstawiają binarne macierze powiązań międzygałęziowych dla wariantu 11 oraz 28.



Rys. 5.1. Struktura gospodarki energetycznej analizowanego budynku dla wariantu 4

Na podstawie binarnej macierzy powiązań międzygałęziowych, zapotrzebowania podsystemu odbiorców na poszczególne nośniki energii oraz identyfikacji procesowej wszystkich urządzeń i instalacji podsystemu energetycznego określa się roczne wartości zużyć wszystkich nośników energii w podsystemie energetycznym oraz wielkość dostaw zewnętrznych dla danego wariantu gospodarki energetycznej. Wyniki analizy wariantu 4 w formie porównania z wariantem przedstawiono na rys. 5.2. Wskutek zainstalowania układu CHP znacznie zmniejszyło się zapotrzebowanie na energię elektryczną. Zwiększeniu uległa dostawa gazu ziemnego, który zużywany jest w kotle szczytowym. Zainstalowanie układu CHP zasilanego olejem napędowym wymaga dostawy tego nośnika energii.



Rys. 5.2. Zmiana wielkości dostaw zewnętrznych nośników energii - porównanie wariantu 4 ze stanem aktualnym budynku (wariant 1)

Przedstawiona procedura pozwoliła na określenie rocznych zużyć wszystkich nośników energii w budynku dla każdego wygenerowanego wariantu gospodarki energetycznej. Wyniki tej analizy mogą posłużyć w dalszym etapie do znalezienia wariantu optymalnego stosując kryterium ekonomiczne bądź ekologiczne.

6. Algorytm oceny systemowej racjonalizacji gospodarki energetycznej kompleksu budowlanego

Analiza systemowa wpływu racjonalizacji energetycznej na gospodarkę energetyczną kompleksu budowlanego oparta jest o metodę bilansową wykorzystującą model matematyczny gospodarki energetycznej kompleksu budowlanego. Realizacja przedsięwzięć racjonalizacyjnych może mieć miejsce bądź w podsystemie energetycznym, bądź w podsystemie odbiorców. Efekty bezpośrednie racjonalizacji są oceniane za pomocą metod procesowych (np. zmiana rozdzielonej gospodarki ciepłno-elektrycznej na skojarzoną gospodarkę ciepłno-elektryczną). Do efektów systemowych dochodzi się poprzez zastosowanie macierzy odwrotnej układu równań bilansowych, której współczynniki ujmują zarówno zużycie bezpośrednie, jak i pośrednie wynikające z powiązań w sieci procesów energetycznych.

Zmiana procesowa w którymkolwiek z ogniw podsystemu energetycznego i podsystemu konsumentów (odbiorców) wpływa na zmiany w pozostałych ogniwach z powodu sieci wzajemnych powiązań jaka istnieje w gospodarce energetycznej kompleksu budowlanego. System powiązań ujmuje układ równań bilansowych (5.11) i (5.13), który dla celów niniejszego rozdziału uproszczono do postaci:

$$\mathbf{G} + \mathbf{F}\mathbf{G} + \mathbf{D}_G = \mathbf{A}_G\mathbf{G} + \mathbf{C}_G \quad (8.1)$$

$$\mathbf{D}_D = \mathbf{A}_D\mathbf{G} + \mathbf{C}_D \quad (8.2)$$

gdzie:

- $\mathbf{G}$ – wektor produkcji głównej,
- $\mathbf{D}_G, \mathbf{D}_D$ – wektory dostaw zewnętrznych uzupełniających i wyłącznych,
- $\mathbf{F}$ – macierz wskaźników ubocznego wytwarzania nośników energii,
- $\mathbf{A}_G, \mathbf{A}_D$ – macierze wskaźników zużycia nośników energii w podsystemie energetycznym dla nośników energii produkowanych i doprowadzanych z zewnątrz,
- $\mathbf{C}_G, \mathbf{C}_D$ – wektory zużycia nośników energii w podsystemie odbiorców, produkowanych jako produkty główne i doprowadzanych z zewnątrz.

W porównaniu z równaniem (5.11) i (5.13) pominięto uboczne wytwarzanie w podsystemie technologicznym oraz przyjęto, że zużycie nośników energii w podsystemie technologicznym (odbiorców) są zadane jako wielkości stałe (wektory $\mathbf{C}_G$ i $\mathbf{C}_D$).

Z równań (8.1) i (8.2) otrzymuje się:

$$\mathbf{G} = (\mathbf{E} - \mathbf{A}_G + \mathbf{F})^{-1} (\mathbf{C}_G - \mathbf{D}_G) \quad (8.3)$$

$$\mathbf{D}_D = \mathbf{A}_D (\mathbf{E} - \mathbf{A} + \mathbf{F})^{-1} (\mathbf{C}_G - \mathbf{D}_G) + \mathbf{C}_D \quad (8.4)$$

Jeżeli zmiana procesowa ma miejsce w podsystemie odbiorców wówczas zmianie ulegają wektory $\mathbf{C}_G$ i $\mathbf{C}_D$. Wówczas mamy:

$$\Delta \mathbf{G} = (\mathbf{E} - \mathbf{A}_G + \mathbf{F})^{-1} [(\mathbf{C}_G - \mathbf{D}_G)'' - (\mathbf{C}_G - \mathbf{D}_G)'] \quad (8.5)$$

$$\Delta \mathbf{D}_D = \mathbf{A}_D \Delta \mathbf{G} + \mathbf{C}_D'' - \mathbf{C}_D' \quad (8.6)$$

Macierz odwrotna $(\mathbf{E} - \mathbf{A}_G + \mathbf{F})^{-1}$ ujmuje cały system wzajemnych powiązań procesów energetycznych tworzących sieć technologiczną. Apostrofy '' i ' oznaczają stan gospodarki energetycznej kompleksu budowlanego po racjonalizacji i przed racjonalizacją.

W przypadku zmian w podsystemie energetycznym zmianie ulegają elementy macierzy $\mathbf{A}$ i $\mathbf{F}$. Wówczas:

$$\Delta \mathbf{G} = [(\mathbf{E} - \mathbf{A}'' + \mathbf{F}'')^{-1} - (\mathbf{E} - \mathbf{A}' + \mathbf{F}')^{-1}] (\mathbf{C}_G - \mathbf{D}_U) \quad (8.7)$$

$$\Delta \mathbf{D}_W = \mathbf{A}_D \Delta \mathbf{G} \quad (8.8)$$

Również i w tym przypadku zmiana macierzy odwrotnej pozwala na ocenę efektów systemowych.

7. Przykład obliczeniowy oceny systemowej racjonalizacji gospodarki energetycznej kompleksu budowlanego

7.1. Zastosowania nocnej wentylacji jako sposobu racjonalizacji gospodarki energetycznej kompleksu budowlanego

Jako przykład racjonalizacji gospodarki energetycznej rozpatrywanego kompleksu budowlanego poddano analizie zastosowanie nocnej wentylacji. Nocna wentylacja należy do niskoenergetycznych sposobów chłodzenia budynków. Polega ona na doprowadzeniu chłodnego powietrza zewnętrznego do budynku w okresie nocnym celem ochłodzenia jego przegród wewnętrznych, które zakumulowały ciepło w ciągu dnia. Wpływ na zmniejszenie zapotrzebowania chłodu dla analizowanego budynku został określony w pozycji za pomocą oprogramowania NiteCool. Wykorzystanie nocnej wentylacji oprócz zmniejszenia zapotrzebowania na chłód powoduje również zmniejszenie zapotrzebowania na energię elektryczną w biurowych, indywidualnych urządzeniach klimatyzacyjnych (krótsza praca wentylatora w klimatyzatorze biurowym). Zastosowanie nocnej wentylacji pozwala również na obniżenie maksymalnej temperatury wewnętrznej w ciągu dnia. Zmiany systemowe spowodowane zmniejszeniem zapotrzebowania na poszczególne nośniki energii po zastosowaniu nocnej wentylacji, powodują zmniejszenie zapotrzebowania na inne nośniki energii, które są wytwarzane w budynku lub dostarczane z zewnątrz.

W analizie rozpatrzono następujące rodzaje nocnej wentylacji:

wentylacja mechaniczna nawiewna,
wentylacja mechaniczna wywiewna,
wentylacja mechaniczna nawiewno-wywiewna,
wentylacja naturalna jednoszczelinowa,
wentylacja naturalna dwuszczelinowa,
wentylacja naturalna nawiewno-wywiewna,
wentylacja naturalna z ciągiem kominowym.

Przewidziano współpracę nocnej wentylacji z istniejącym w budynku systemem klimatyzacji opartym na indywidualnych klimatyzatorach, połączonych instalacją wody lodowej z centralnym agregatem chłodniczym.

Uwzględniono następujące parametry odpowiedzialne za efektywność nocnej wentylacji:

temperatura zewnętrzna,
prędkość i kierunek wiatru,
powierzchnie szczelin na cele nocnej wentylacji,

różnica wysokości szczelin wentylacyjnych w pomieszczeniach.

Wielkości poszczególnych danych wejściowych do analizy wpływu nocnej wentylacji na zapotrzebowanie chłodu zebrano w tablicy 7.1.

Tablica 7.1. Wybrane dane wejściowe do analizy wpływu nocnej wentylacji na zmniejszenie zapotrzebowania chłodu w analizowanym budynku

Parametr	Wartość
Wewnętrzne zyski ciepła	55 W/m ²
Infiltracja	0,5 w/h
Orientacja geograficzna budynku	270°
Rodzaj konstrukcji (lekka, średnia, ciężka)	średnia
Stosunek oszklenia	0,7
Rodzaj terenu	obszar miejski
Wysokość budynku	24m
Kierunek i prędkość wiatru	Dane statystyczne programu NiteCool dla wybranego obszaru
Kąt pochylenia dachu	<11°
Czas pracy nocnej wentylacji	24:00-07:00
System klimatyzacji	System klimatyzacji oparty na indywidualnych klimatyzatorach, połączonych instalacją wody lodowej z centralnym agregatem chłodniczym
Liczba wymian powietrza	5 w/h
COP	3
Moce wentylatorów w centrali klimatyzacyjnej	15kW, 11kW

Przeanalizowano wszystkie strategie nocnej wentylacji uzyskując dobowe wykresy temperatury oraz oszczędności w zapotrzebowaniu na chłód w poszczególnych miesiącach. Najbardziej efektywnym rodzajem nocnej wentylacji dla warunków analizowanego budynku okazała się naturalna wentylacja nawiewno-wywiewna, którą wzięto do dalszych rozważań z uwagi na duże zużycie energii elektrycznej przez wentylatory. Wymienione rodzaje nocnej wentylacji mechanicznej okazały się nieuzasadnione dla danego rodzaju i lokalizacji budynku. Przeprowadzono analizę optymalizacyjną ze względu na czas działania

nocnej wentylacji oraz liczbę wymian powietrza wentylacyjnego. W celu określenia wpływu poszczególnych parametrów na obniżenie zapotrzebowania chłodu przeprowadzono analizę wrażliwości. Najbardziej znaczący wpływ na uzyskiwane oszczędności w zapotrzebowaniu chłodu ma rodzaj konstrukcji budynku oraz liczba wymian powietrza wewnętrznego. Analiza wykazała, że najbardziej optymalna dla analizowanego budynku nocna wentylacja nawiewno-wywiewna wpłynęła na obniżenie zapotrzebowania na chłód o 63,51 GJ rocznie.

Zmiany systemowe spowodowane zmniejszeniem zapotrzebowania na poszczególne nośniki energii po zastosowaniu nocnej wentylacji powodują zmniejszenie zapotrzebowania na inne nośniki energii, które są wytwarzane w budynku lub dostarczane z zewnątrz. Na skutek zastosowania nocnej wentylacji w budynku uległ zmianie wektor zapotrzebowania **C**. Wektor ΔC zmian zapotrzebowania ma postać:

$$\Delta C = \begin{bmatrix} -63,51 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -9 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Po uwzględnieniu wektora ΔC określono nowe wartości zużyć poszczególnych nośników energii, które ujęto w tablicach 7.2 i 7.3. Tablice te przedstawiają zmiany systemowe spowodowane zmniejszonym zapotrzebowaniem na chłód i energię elektryczną.

W analizowanym przykładzie modernizacji podsystemu odbiorców struktura gospodarki energetycznej rozpatrywanego kompleksu budowlanego nie uległa zmianie. Podsystem odbiorców współczesnych kompleksów budowlanych jest mniej złożony pod względem liczby powiązań międzygałęziowych w stosunku do podsystemu energetycznego. Mimo to, istnieje wciąż wiele sposobów racjonalizacji podsystemu odbiorców w celu zwiększenia efektywności wykorzystania energii w budynku.

Tablica 7.2. Zastosowanie nocnej wentylacji w budynku - tablica wskaźników zużycia nośników energii

Ip.	Nośnik energii	JED.	PRODUKCJA	DOSTAWA	PRZEPŁYWY MIĘDZYGAŁĘZIOWE									
					PODSYSTEM ENERGETYCZNY						PODSYSTEM ODBIORCÓW			
					1	2	3	4	5	6	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodniczy 6/12 C	GJ	1064,99		0	0	0	0	0,000919	0	995,23	0	0	0
2	Goraca woda procesowa 85/45 C	GJ	1827,98		0	0	0	0	0,01286	0	0	851,8	0	0
3	CWU	Mg	994,60		0	0	0	0	0	0	0	994,6	0	0
4	Goraca woda procesowa 60/45 C	GJ	1677,11		0	0	0	0	0	0	1677,11	0	0	0
5	Powietrze z centrali klimatyzacyjnej	Mg	75908,00		0	0	0	0	0	0	45544,8	30363,2	0	0
6	Powietrze wentylacyjne	Mg	435591,00		0	0	0	0	0	0	0	0	435591	0
7	Ciepło grzejne	GJ		3675,66	0	1	0,1715	1	0	0	0	0	0	0
8	Energia elektryczna	GJ		4584,06	0,4858	0,02413	0,00364	0,004699	0,003556	0,00089	2630,22	79,22	397,33	246,7
9	Gaz ziemny	GJ		576,00	0	0	0	0	0	0	0	576	0	0
10	Woda wodociągowa	Mg		11079,60	0	0	1	0	0	0	0	10085	0	0

Tablica 7.3. Zastosowanie nocnej wentylacji w budynku - tablica wartości zużyć poszczególnych nośników energii w gałęziach energetycznych

Ip.	Nośnik energii	JED.	PRODUKCJA	DOSTAWA	PRZEPŁYWY MIĘDZYGAŁĘZIOWE									
					PODSYSTEM ENERGETYCZNY						PODSYSTEM ODBIORCÓW			
					1	2	3	4	5	6	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodniczy 6/12 C	GJ	1064,99		0	0	0	0	69,75945	0	995,23	0	0	0
2	Goraca woda procesowa 85/45 C	GJ	1827,98		0	0	0	0	976,1769	0	0	851,8	0	0
3	CWU	Mg	994,60		0	0	0	0	0	0	0	994,6	0	0
4	Goraca woda procesowa 60/45 C	GJ	1677,11		0	0	0	0	0	0	1677,11	0	0	0
5	Powietrze z centrali klimatyzacyjnej	Mg	75908,00		0	0	0	0	0	0	45544,8	30363,2	0	0
6	Powietrze wentylacyjne	Mg	435591,00		0	0	0	0	0	0	0	0	435591	0
7	Ciepło grzejne	GJ		3675,66	0	1827,977	170,5739	1677,11	0	0	0	0	0	0
8	Energia elektryczna	GJ		4584,06	517,3719	44,10908	3,620344	7,88074	269,9288	387,676	2630,22	79,22	397,33	246,7
9	Gaz ziemny	GJ		576,00	0	0	0	0	0	0	0	576	0	0
10	Woda wodociągowa	Mg		11079,60	0	0	994,6	0	0	0	0	10085	0	0

7.2. Modernizacja gospodarki energetycznej kompleksu budowlanego przez zastosowanie małego układu skojarzonego

W przypadku zmiany rozdzielonej gospodarki ciepłno-elektrycznej na gospodarkę skojarzoną wektory C_G i C_D zużyć nośników energii w podsystemie odbiorców nie ulegają zmianie. Zmianie ulegają natomiast elementy macierzy powiązań międzygałęziowych A_G i A_D oraz macierzy F ubocznego wytwarzania nośników energii.

W rozważanym kompleksie budowlanym wystąpił przypadek ubocznego wytwarzania energii elektrycznej. Przyjęto bowiem wzorem klasycznej elektrociepłowni, że ciepło jest produktem głównym. Ciepło produkowane w układzie CHP w całości jest zużywane na potrzeby budynku. W okresach zwiększonego zapotrzebowania ciepło produkowane jest również w gazowym kotle szczytowym. Wskaźnik ubocznego wytwarzania energii elektrycznej wynika ze wskaźnika skojarzenia σ :

$$f_{87} = (1 - \varepsilon)\sigma$$

gdzie ε oznacza udział ciepła szczytowego w całkowitej produkcji ciepła.

Uboczna produkcja energii elektrycznej U_{87} jest obliczana za pomocą równania:

$$U_{87} = f_{87} G_7 = (1 - \varepsilon) \sigma G_7 \quad (8.9)$$

gdzie G_7 oznacza całkowitą produkcję ciepła w analizowanym budynku.

Zużycie energii chemicznej gazu ziemnego na produkcję energii elektrycznej jest obliczane na podstawie zasady unikniętych nakładów paliwowych. Zasada ta, sformułowana na wzór metody kosztów unikniętych mówi, że produkcję energii elektrycznej w układzie skojarzonym należy obciążyć takim zużyciem energii chemicznej paliwa jakie ma miejsce w elektrowni zastapionej, w której powinno się wytworzyć równoważną ilość energii elektrycznej. Stąd otrzymuje się:

$$Z_{98} = \frac{U_{87}}{\eta_{Elg}} \quad (8.10)$$

gdzie:

Z_{98} – zużycie energii chemicznej gazu na produkcję energii elektrycznej w rozważanym układzie CHP,

$\eta_{El g}$ – sprawność energetyczna równoważnej (zastąpionej) elektrowni gazowej.

Zużycie energii chemicznej gazu na produkcję ciepła oblicza się wówczas z równania:

$$Z_{97} = \frac{(1-\varepsilon)G_7 + U_{87}}{\eta_{E\,CHP}} + \frac{\varepsilon G_7}{\eta_{E\,k\,sz}} - \frac{U_{87}}{\eta_{El g}} \quad (8.11)$$

stąd wskaźnik jednostkowego zużycia energii chemicznej gazu na produkcję ciepła

$$a_{97} = \frac{Z_{97}}{G_7} = \frac{(1-\varepsilon)(1+\sigma)}{\eta_{E\,CHP}} + \frac{\varepsilon}{\eta_{E\,k\,sz}} - \frac{(1-\varepsilon)\sigma}{\eta_{El g}} \quad (8.12)$$

gdzie:

$\eta_{E\,CHP}$ – sprawność energetyczną rozpatrywanego układu CHP w budynku,

$\eta_{E\,k\,sz}$ – sprawność energetyczna gazowego kotła szczytowego.

Oszczędność energii chemicznej gazu uzyskana dzięki gospodarce skojarzonej ciepłno-elektrycznej:

$$-\Delta E_{ch} = \frac{(1-\varepsilon)G_7}{\eta_{E\,c\,g}} + \frac{U_{87}}{\eta_{El g}} - \frac{(1-\varepsilon)G_7 + U_{87}}{\eta_{E\,CHP}} \quad (8.13)$$

gdzie $\eta_{E\,c\,g}$ to sprawność energetyczna ciepłowni zasilanej gazem ziemnym.

W odniesieniu do jednostki produkowanego ciepła otrzymuje się:

$$\frac{-\Delta E_{ch}}{G_7} = (1-\varepsilon) \left(\frac{1}{\eta_{E\,c\,g}} + \frac{\sigma}{\eta_{El g}} - \frac{1+\sigma}{\eta_{E\,CHP}} \right) \quad (8.14)$$

Wskaźnik PES względnej oszczędności energii chemicznej paliw pierwotnych:

$$PES = \frac{-\Delta E_{ch}}{E_{chr}} \quad (8.15)$$

gdzie E_{chr} oznacza energię chemiczną w gospodarce rozdzielonej.

$$PES = 1 - \frac{\frac{1+\sigma}{\eta_{E\,CHP}}}{\frac{1}{\eta_{E\,c\,g}} + \frac{\sigma}{\eta_{El g}}} \quad (8.16)$$

W przypadku analizowanego kompleksu budowlanego, dla założeń zebranych w tablicy 8.4 wskaźnik względnej oszczędności energii pierwotnej wynosi $PES=0,31$.

Skumulowaną oszczędność energii chemicznej paliwa ujmuje równanie:

$$-\Delta E_{ch}^* = \frac{-\Delta E_{ch}}{\eta_{pdg}^*} \quad (8.17)$$

gdzie: η_{pdg}^* oznacza sprawność skumulowaną pozyskania i dostawy gazu ziemnego.

Na potrzeby modernizacji gospodarki energetycznej analizowanego budynku zaproponowano zainstalowanie układu CHP bazującego na tłokowym silniku spalinowym. Dane wejściowe do tej analizy przedstawiono w tablicy 7.4.

Tablica 7.4. Dane wejściowe do analizy aplikacji układu CHP

Zapotrzebowanie na ciepło dla budynku	$Q=3675,66 \text{ GJ/rok}$
Wskaźnik skojarzenia w układzie CHP	$\sigma=0,65$
Sprawność energetyczna układu CHP	$\eta_{E\text{ CHP}} = 0,77$
Sprawność energetyczna gazowego kotła szczytowego	$\eta_{E\text{ k sz}} = 0,85$
Udział ciepła szczytowego w całkowitej produkcji ciepła	$\varepsilon=0,1$
Sprawność energetyczna ciepłowni zasilanej gazem ziemnym	$\eta_{E\text{ cg}} = 0,85$
Sprawność energetyczna zastąpionej elektrowni zasilanej gazem ziemnym	$\eta_{E\text{ el g}} = 0,339$

Wyniki analizy - wskaźniki zużycia nośników energii oraz wielkości zużyć w gałęziach energetycznych przedstawiono w tablicy 7.5 i 7.6.

Zaprezentowany przykład obliczeniowy racjonalizacji gospodarki energetycznej kompleksu budowlanego poprzez zainstalowanie układu CHP pokazuje, iż w takim przypadku zmiana ulega struktura podsystemu energetycznego. Struktura zużycia nośników energii po stronie odbiorców nie ulega zmianie (co miało miejsce w przypadku zastosowania nocnej wentylacji w budynku – punkt 7.1). Jak pokazały obliczenia w

przykładzie zmniejszeniu uległo zapotrzebowanie na energię elektryczną do budynku, która jest wytwarzana ubocznie w układzie CHP. Wytwórczość energii elektrycznej w układzie skojarzonym przynosi efekt w postaci zmniejszenia zużycia energii chemicznej paliwa w porównaniu z gospodarką rozdzieloną. W rozpatrywanym przypadku skumulowana oszczędność energii chemicznej paliwa wynosi $-\Delta E_{ch}^* = 3210 \text{ GJ}$. Wartość wskaźnika $PES=0,31$ świadczy o wysokiej efektywności energetycznej zastosowanej modernizacji gospodarki energetycznej kompleksu budowlanego.

Tablica 7.5. Zastosowanie układu CHP w budynku - tablica wskaźników zużycia nośników energii

Ip.	Nośnik energii	JED.	PRODUKCJA	DOSTAWA	PRZEPŁYWY MIĘDZYGAŁĘZIOWE										PODSYSTEM ODBIORCÓW			
					1	2	3	4	5	6	7	8	9	10	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodniczy 6/12 C	GJ	1128.339452		0	0	0	0	0.000919	0	0	0	0	0	1058.58	0	0	0
2	Goraca woda procesowa 85/45 C	GJ	1827.97688		0	0	0	0	0.01286	0	0	0	0	0	0	851.8	0	0
3	CWU	Mg	994.6		0	0	0	0	0	0	0	0	0	0	0	994.6	0	0
4	Goraca woda procesowa 60/45 C	GJ	1677.11		0	0	0	0	0	0	0	0	0	0	1677.11	0	0	0
5	Powietrze z centrali klimatyzacyjnej	Mg	75908		0	0	0	0	0	0	0	0	0	0	45544.8	30363.2	0	0
6	Powietrze wentylacyjne	Mg	435591		0	0	0	0	0	0	0	0	0	0	0	0	435591	0
7	Ciepło grzejne	GJ	3675.66078		0	1	0.1715	1	0	0	0	0	0	0	0	0	0	0
8	Energia elektryczna	GJ	2150	2516.84231	0.4858	0.02413	0.00364	0.004699	0.003556	0.00089	0	0.020005	0	0	2639.22	79.22	397.33	246.7
9	Gaz ziemny	GJ		8097	0	0	0	0	0	0	2.046163	0	0	0	0	576	0	0
10	Woda wodociągowa	Mg		11079.6	0	0	1	0	0	0	0	0	0	0	0	10085	0	0

Tablica 7.6. Zastosowanie układu CHP w budynku - tablica wartości zużyć poszczególnych nośników energii w gałęziach energetycznych

Ip.	Nośnik energii	JED.	PRODUKCJA	DOSTAWA	PRZEPŁYWY MIĘDZYGAŁĘZIOWE										PODSYSTEM ODBIORCÓW			
					1	2	3	4	5	6	7	8	9	10	Pomieszczenia biurowe	Pomieszczenia ogólnego przeznaczenia	Garaże	Standardowe wyposażenie budynku
1	Czynnik chłodniczy 6/12 C	GJ	1128.339452		0	0	0	0	69.75945	0	0	0	0	0	1058.58	0	0	0
2	Goraca woda procesowa 85/45 C	GJ	1827.97688		0	0	0	0	976.1769	0	0	0	0	0	0	851.8	0	0
3	CWU	Mg	994.6		0	0	0	0	0	0	0	0	0	0	0	994.6	0	0
4	Goraca woda procesowa 60/45 C	GJ	1677.11		0	0	0	0	0	0	0	0	0	0	1677.11	0	0	0
5	Powietrze z centrali klimatyzacyjnej	Mg	75908		0	0	0	0	0	0	0	0	0	0	45544.8	30363.2	0	0
6	Powietrze wentylacyjne	Mg	435591		0	0	0	0	0	0	0	0	0	0	0	0	435591	0
7	Ciepło grzejne	GJ	3675.66078		0	1827.977	170.5739	1677.11	0	0	0	0	0	0	0	0	0	0
8	Energia elektryczna	GJ	2150	2516.84231	548.1473	44.10908	3.620344	7.88074	269.9288	387.676	0	43.01	0	0	2639.22	79.22	397.33	246.7
9	Gaz ziemny	GJ		8097	0	0	0	0	0	0	7521	0	0	0	0	576	0	0
10	Woda wodociągowa	Mg		11079.6	0	0	994.6	0	0	0	0	0	0	0	0	10085	0	0

8. Charakterystyka utworzonych kodów komputerowych w ramach prac w Etapie nr 8 „Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej” przewidzianych do implementacji w programie integracyjnym

Etap nr 8 projektu obejmował swoim zakresem działalność badawczą polegającą na zastosowaniu metody systemowej do analizy energetyczno-ekologicznej kompleksu budowlanego użyteczności publicznej.

Opracowane algorytmy mogą stanowić oddzielny moduł w programie integracyjnym obejmujący analizę energetyczno-ekologiczną budynku użyteczności publicznej.

8.1. Opracowane algorytmy

Algorytmy opracowane w ramach Etapu 8:

- algorytm określania wskaźników bezpośredniego zużycia energii w budynku,
- algorytm skumulowanego zużycia energii,
- algorytm skumulowanej emisji zanieczyszczeń,
- algorytm rachunku kosztu termoeekologicznego (uciążliwości środowiskowej),
- moduł zautomatyzowanych algorytmów odpowiedzialnych za utworzenie wariantów sieci powiązań energetycznych i technologicznych w budynku (optymalizacja struktury gospodarki energetycznej budynku).

8.2. Charakterystyka danych wejściowych do analizy

Dane wejściowe do analiz stanowią:

1. Wielkości zapotrzebowania na poszczególne nośniki energii w podsystemie odbiorców. Mogą one być wynikiem analiz i symulacji uzyskanych w innych etapach, np. zapotrzebowanie na ciepło, zapotrzebowanie na c.w.u, zapotrzebowanie chłodu, strumień powietrza klimatyzacyjnego, itd. Alternatywnie można przewidzieć możliwość wprowadzania tych wielkości bezpośrednio przez użytkownika. Dane wprowadzane są w formie wektorów, każdy wektor odpowiada wyodrębnionej grupie pomieszczeń w podsystemie odbiorców. Wiersze odpowiadają zużyciu określonego nośnika energii. Liczba wektorów nie więcej niż 30, wymiar nie większy niż 50x1.
2. Binarne macierze powiązań międzygałęziowych w podsystemie energetycznym i podsystemie odbiorców. Wymiary macierzy (nie większe niż 50x50).
3. Macierze wskaźników bezpośredniego zużycia/produkcji nośników energii w podsystemie energetycznym i podsystemie odbiorców. Wymiary macierzy (nie

większe niż 50x50). Wskaźniki bezpośredniego zużycia/produkcji wynikają z symulacji bądź pomiarów urządzeń energetycznych w budynku.

4. Wektory wskaźników skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz kosztu termo-ekologicznego dla nośników energii dostarczanych z zewnątrz. Wskaźniki te stanowią wewnętrzną bazę danych modułu. Użytkownik po wybraniu danego nośnika energii, który będzie dostarczany z zewnątrz do budynku przyporządkuje automatycznie odpowiedni wskaźnik (np. wskaźnik skumulowanego zużycia energii dla dostarczanej elektryczności, wskaźniki emisyjne dla biomasy, itd.).

8.3. Charakterystyka uzyskiwanych wyników

Wyniki opracowanej metodyki stanowią:

1. Wektory zapotrzebowania na nośniki energii, które są produkowane w budynku oraz dostarczane z zewnątrz (produkcja szczytowa i podstawowa).
2. Macierze zużyć/produkcji poszczególnych nośników energii w gałęziach energetycznych i w podsystemie odbiorców. Analogicznie dla skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz kosztu termo-ekologicznego.
3. Wektory wskaźników skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz kosztu termo-ekologicznego dla wszystkich nośników energii w budynku.
4. Wyniki dla wybranego okresu bilansowania przedstawione zostaną na wykresach i w tablicach. Wszelkie wymagania dotyczące prezentacji wyników zostaną dostarczone wykonującemu program integracyjny.
5. Proponowany okres bilansowania na potrzeby analizy energetyczno-ekologicznej to 1 rok, bądź ewentualnie 1 miesiąc. Założenie krótkich okresów bilansowania jest możliwe ale pociąga za sobą konsekwencję znacznego zwiększenia liczby wprowadzanych danych w finalnej aplikacji komputerowej.

8.4. Wykorzystane narzędzia informatyczne

Do zaprogramowania opracowanych algorytmów wykorzystano następujące narzędzia informatyczne:

- Język programowania Visual Basic (automatyzacja obliczeń i komunikacja pomiędzy podmodułami)
- MS Excel (baza wiedzy oraz rozwiązywanie zagadnień liniowych)

- EES - Engineering Equation Solver (symulacje i analiza zagadnień nieliniowych)

Pakiet arkuszy kalkulacyjnych wykonany w MS Excel, obejmujący analizę dla przykładowego budynku przedstawiono w Załączniku nr 6.

Moduł zautomatyzowanych algorytmów odpowiedzialnych za utworzenie wariantów sieci powiązań energetycznych i technologicznych w budynku został zamieszczony w Załączniku nr 2. Moduł ten działa w oparciu o język programowania Visual Basic współpracujący z oprogramowaniem Microsoft Excel.

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Mathematical model for the simulation of cumulative emissions generated by energy management of complex buildings

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Abstract:

Buildings play a leading part in direct and indirect emissions of noxious substances to the environment, among others CO₂. In the worldwide emissions of greenhouse gases, the building sector has a share of 40%. It is one of the fastest growing sources. Modern complex buildings use many kinds of complicated energy devices and installations, like CHPs, trigeneration, air conditioning, heating, etc. The operation of the energy management of such buildings requires consumption and production of energy carriers within interconnected energy processes. Energy processes are responsible for emissions generated directly by the building and these are connected with energy carriers which are supplied to the building from outside. The sum of direct and indirect emissions is called cumulative emissions. This paper deals with the problem of modelling both direct and indirect emissions generated within interconnected processes of energy production and supply. For the purpose of modelling the energy management of a building the input-output analysis has been applied. The proposed mathematical model allows to calculate the coefficients of cumulative emissions for all considered energy carriers in complex buildings. It may be helpful in appropriate designing of complex buildings and leads to emission reductions in the building sector. The developed mathematical model has been applied in the analysis of a particular office building.

Keywords:

Complex buildings, cumulative emissions, mathematical modelling.

1. Introduction

Modern complex buildings, such as office buildings, hospitals, supermarkets, hotels, etc., demand a rich gamut of different energy carriers to achieve thermal comfort and process needs in the case of technological equipment. Some of them are delivered from outside, the rest being produced in the building by its energy equipment and installations. Production, transport, preparation and consumption of each energy carrier cause emissions of noxious substances to the environment. In the past, most energy carriers were supplied to complex buildings from external central energy systems. Their energy management structures were rather simple, and ecological analyses of such buildings were not complicated. Rising standards of the rational use of energy require the application of new devices and technologies in such buildings. Therefore, today's buildings are complicated energy systems, the ecological analysis of which is not as simple as in the past. The mathematical model presented in this paper allows to calculate the cumulative emissions generated by all energy branches in the building. It may be applied both for aiding the design of complex buildings and in the energy-ecological analysis of their exploitation [7].

2. System approach to the analysis of complex buildings

The use of final energy carriers in complex buildings is inseparably connected with emissions of noxious substances to the environment. Final energy carriers are used in complex buildings to provide a variety of services, such as lighting, space heating, water heating, space cooling, refrigeration, dehumidification and electricity for internal equipment. Energy management of complex buildings can be considered to consist of two basic subsystems: the energy subsystem (production of energy carriers) and the subsystem of consumers. The energy subsystem serves for

the production, conversion, transmission and distribution of energy carriers consumed in the subsystem of consumers. The flow of energy carriers from the energy subsystem to the subsystem of consumers can be presented in the form of an interbranch table (Table 1). The structure of this table is based on the following principles:

- the energy subsystem is divided into production branches; to each branch corresponds one energy carrier,
- the energy carrier may be the main product of the given branch, a by-product of some other branch or be supplied from outside,
- the energy carriers are consumed completely inside the balance cover shield of complex buildings; mainly for the needs of the subsystem of consumers and partly for the requirements of the energy subsystem.

The mathematical model of complex buildings is a set of equations resulting from the balance of all energy carriers formulated on the basis of input-output analysis [1-4,6]. It comprises a network of interdependences, existing in a real complex building between the consumers and the energy subsystems as well as inner relations between the energy processes. A general principle of the mathematical model is the assumption concerning the linear dependence between the production and consumption of energy carriers. In complex buildings the rate of production by the energy subsystem depends on the demand for energy carriers in the subsystem of consumers (for example: the users' needs) and the own needs resulting from connections between the energy branches [5].

The energy branch in complex buildings is defined as a group of devices and equipment of the energy subsystem producing specific energy carriers, for example the central heating system, cooling system or ventilation system. The consumer branch is defined as a group of rooms, devices and equipment of the subsystem of consumers, which consume energy from the energy subsystem, for example offices, auxiliary rooms.

Table 1. Input-output table of interbranch flows of energy carriers in building

Energy carrier	Input part				Output part	
	Main production	By-production		External supply	Interbranch flows	
		Energy subsystem	Subsystem of consumers		Energy subsystem	Subsystem of consumers
1	G_1	$\sum_{j=1}^n U_{1j}$	$\sum_{k=1}^p \bar{U}_{1k}$	D_{G1}	$\sum_{j=1}^n Z^{G_{1j}}$	$\sum_{k=1}^p \bar{Z}^{G_{1k}}$
...	...	...	...	...	...	...
i	G_i	$\sum_{j=1}^n U_{ij}$	$\sum_{k=1}^p \bar{U}_{ik}$	D_{Gi}	$\sum_{j=1}^n Z^{G_{ij}}$	$\sum_{k=1}^p \bar{Z}^{G_{ik}}$
...	...	...	...	...	...	...
n	G_n	$\sum_{j=1}^n U_{nj}$	$\sum_{k=1}^p \bar{U}_{nk}$	D_{Gn}	$\sum_{j=1}^n Z^{G_{nj}}$	$\sum_{k=1}^p \bar{Z}^{G_{nk}}$
$n+1$	G_{n+1}	$\sum_{j=1}^n U_{n+1j}$	$\sum_{k=1}^p \bar{U}_{n+1k}$	D_{Gn+1}	$\sum_{j=1}^n Z^{G_{n+1j}}$	$\sum_{k=1}^p \bar{Z}^{G_{n+1k}}$
...	...	...	...	...	...	...
i	0	0	0	D_{Di}	$\sum_{j=1}^n Z^{D_{ij}}$	$\sum_{k=1}^p \bar{Z}^{D_{ik}}$
...	...	...	...	...	...	...

m	0	0	0	D_{Dm}	$\sum_{j=1}^n Z_{mj}^D$	$\sum_{k=1}^p \bar{Z}_{mk}^D$

All balance equations for energy carriers gathered in the input-output table (Table 1) are formulated on the basis of energy flow chart of the analyzed building. Example of such energy flow chart of analyzed office building is presented in Fig. 2.

In matrix notation the set of balance equations presented in Table 1 has the form:

$$\mathbf{G} + \mathbf{F}\mathbf{G} + \overline{\mathbf{F}}\overline{\mathbf{G}} + \mathbf{D}_G = \mathbf{A}_G \mathbf{G} + \overline{\mathbf{A}}_G \overline{\mathbf{G}} \quad (1)$$

$$\mathbf{D}_D = \mathbf{A}_D \mathbf{G} + \overline{\mathbf{A}}_D \overline{\mathbf{G}} \quad (2)$$

From the matrix Eq. (1) and (2) usually vector $\mathbf{G}$ main production is calculated.

3. Mathematical model of the analysis of cumulative emissions in complex buildings

The operation of complex buildings generates direct and indirect emissions of noxious substances to the environment. These emissions should be minimized by an appropriate design and exploitation of the buildings. Cumulative emissions of noxious substances can be used as a measure of the influence of the building on the environment. Cumulative emissions can be defined as the sum of direct and indirect emissions in the course of production, transport, preparation and consumption of energy carriers which are essential for the operation of the building. Indices of cumulative emissions can be calculated by means of the set of linear energy balances of the building. The concept of the balance of cumulative emissions in a building is presented in Fig. 1.

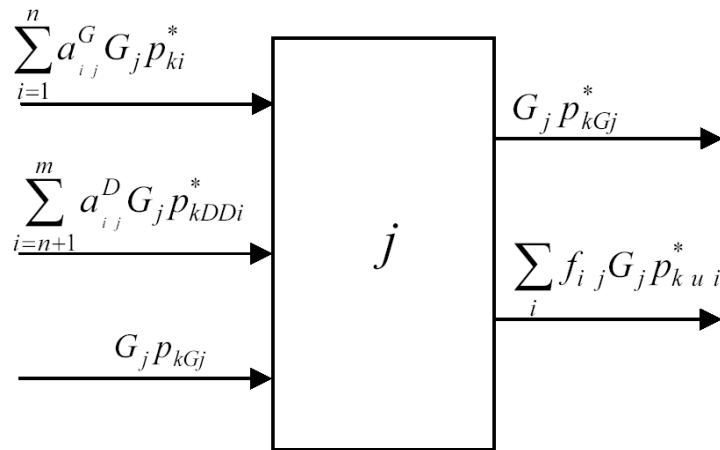


Fig. 1. Flow chart of cumulative emissions in a building

The average-weighted coefficient of cumulative emissions of the k -th kind emission charging the i -th main product is calculated by means of the following formula:

$$p_{ki}^* = r_{Gi} p_{kGi}^* + r_{Ui} p_{kui}^* + r_{Di} p_{kDG_i}^* \quad (3)$$

where:

r_{Gi} , r_{Ui} , r_{Di} - the share of main production, by-production and external supply in k-th emission of it-th energy carrier.

Taking into account relations for shares of main production, by-production and external supply the average-weighted coefficient of cumulative emissions can be written in the following way:

$$p_{ki}^* = \frac{G_i p_{kGi}^* + \left(\sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k \right) p_{kui}^* + D_{Gi} p_{kDG_i}^*}{G_i + \sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k + D_{Gi}} \quad (4)$$

In matrix notation:

$$\mathbf{p}_k^* = \mathbf{H}^{-1} \left\{ \mathbf{G}^d \mathbf{p}_{kG}^* + \left[(\mathbf{F}\mathbf{G})^d + (\bar{\mathbf{F}}\bar{\mathbf{G}})^d \right] \mathbf{p}_{ku}^* + \mathbf{D}_G^d \mathbf{p}_{kDG}^* \right\} \quad (5)$$

where:

$$\text{Error! Objects cannot be created from editing field codes.} \quad (6)$$

Based on the idea presented at Fig. 1. the input-output cumulative emission balance equation concerning the j-th energy branch in complex buildings takes the form:

$$\text{Error! Objects cannot be created from editing field codes.} \quad (7)$$

The matrix Eq. 6 is used to calculate the vector p_{kG}^* of cumulative k-th emission concerning the main production of energy carriers, the vector p_k^* of the average-weighted coefficients of cumulative k-th emissions being determined by Eq. 5. The vectors of cumulative k-th emissions p_{kDG}^* and p_{kDD}^* connected with external supplies are given a priori previously determined basing on the analysis of cumulative emissions on the all over the country. The vector of cumulative k-th emissions p_{ku}^* concerning the by-production is determined in compliance with the principal of avoided emissions.

4. Sample calculations

An exemplary balance of cumulated emissions of noxious substances has been carried out for the variant of energy management concerning the considered complex building, making use of the CHP system based on a gas microturbine. The analysis bases on the mathematical model of calculating the indices of cumulative emissions of noxious substances, dealt with in the preceding paper. In the analysed example of calculations the emission of NOx compounds have been considered. The input data to this procedure are results of the annual balance of the direct consumption of energy in the analyzed complex buildings, indices of cumulated emissions charging the energy carriers supplied to the complex buildings from outside, as well as the quantity of direct emissions resulting from energy and technological processes.

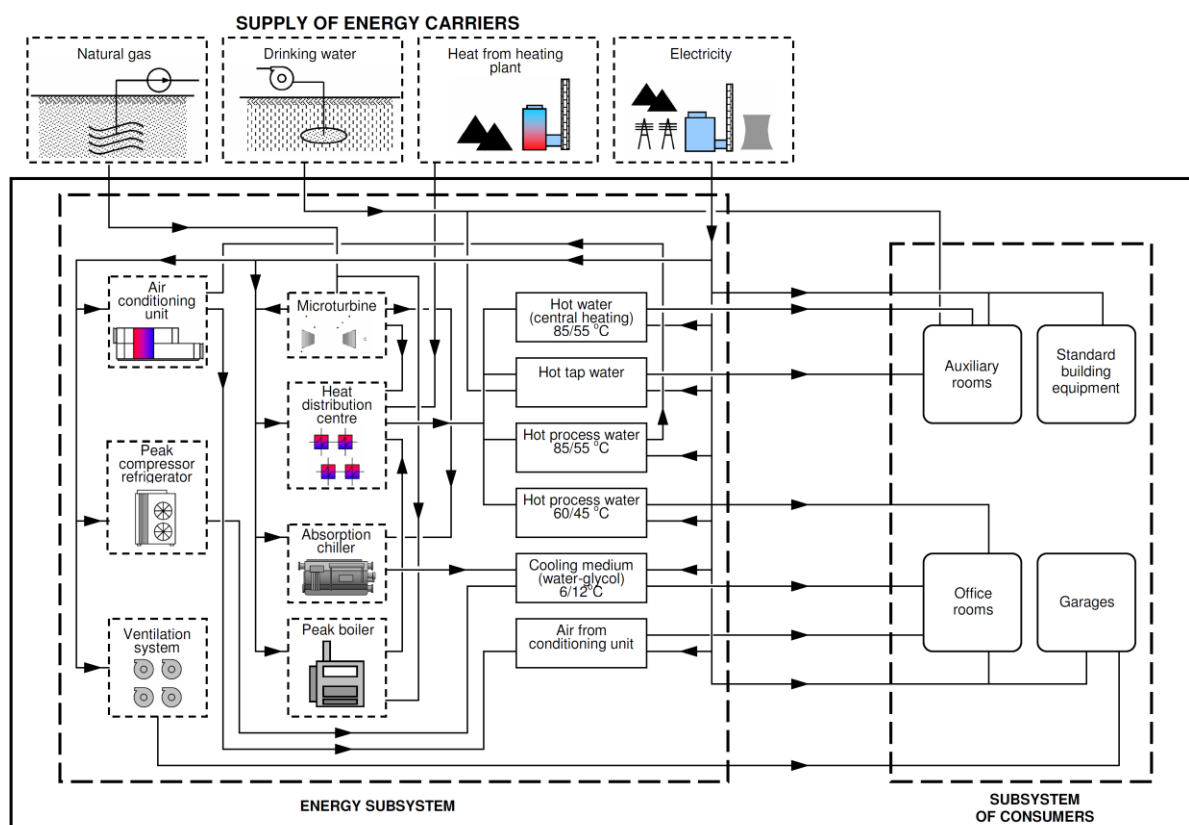


Fig. 2. Subsystems and interbranch flows of energy carriers in analyzed building

The analysis takes into account the effect of replacing electricity produced from the same fuel in a gas power station by electricity produced in a CHP unit, taking into account the efficiency of transformation and transmission of electricity to the complex buildings.

For the purpose of the presented analysis the indices of cumulative NOx emissions have been determined for energy carriers supplied from outside (Table 2). The emission connected with the output and delivery of natural gas to the building have been left out of account. Basing on the process analysis the indices of direct emissions in the energy branches of complex buildings have been determined. The direct emissions of noxious substances in the energy subsystem of the analyzed complex buildings take place in a CHP system and peak-boiler fired with natural gas.

In the case of CHP the value of the index of direct NOx emission per heat production has been assumed on the level of 0.0884 kg/GJ_H (data provided by the producer). In the case of a peak-boiler the following value of this index has been taken into account, viz. 0.005556 kg/GJ_H (data provided by the producer). All the input data for this analysis have been gathered in Table 2.

Table 2. Input data for the analysis of cumulative emissions in the analysed building

Coefficient of the cumulative NOx emission concerning electricity produced in a gas system power plant	$P_{delg}^* = 0,136 \text{ (kg/GJ}_{el}\text{)}$
Coefficient of the cumulative NOx emission concerning electricity produced in system power plant	$P_{dels}^* = 0,4861 \text{ (kg/GJ}_{el}\text{)}$
Coefficient of the cumulative NOx emission concerning the extraction and supply of drinking water to the building	$P_{dw}^* = 0,003936 \text{ (kg/Mg)}$
Coefficient of the direct NOx emission per heat production for CHP unit [8]	$p_{b\text{ CHP}} = 0,0884 \text{ kg/GJ}_H$
Coefficient of the direct NOx emission per heat production for	$p_{b\text{ ksz}} = 0,005556 \text{ kg/GJ}_H$

peak heating boiler [8]

Annual heat production in the CHP unit

$$Q_{CHP}=3308 \text{ GJ/year}$$

Annual peak heat production in the building

$$Q_{k\text{ sz}}=367,6 \text{ GJ/year}$$

Annual by-production of electricity in the CHP unit

$$U_8=2150 \text{ GJ/year}$$

Heat demand for the building

$$Q=3675,66 \text{ GJ/year}$$

CHP coefficient [8]

$$\sigma=0,65$$

Energy efficiency of the CHP unit [8]

$$\eta_{E\text{ CHP}} = 0,77$$

Energy efficiency of the gas peak heating boiler [8]

$$\eta_{E\text{ k sz}} = 0,85$$

Share of peak heat to the overall heat production

$$\varepsilon=0,1$$

Energy efficiency of the heating plant fired with natural gas [9]

$$\eta_{E\text{ c g}} = 0,85$$

Energy efficiency of the substituted gas power station [9]

$$\eta_{E\text{ el g}} = 0,339$$

The considered case concerns the by-production of electricity in the CHP unit, assuming that heat is the main product. Therefore, the charging of heat by emissions of noxious substances ought to be reduced by the emission connected with the replacement of the production of electricity by supplies from a system power station. The example concerns the emission of NOx. The diagram of the balance of cumulated NOx emission connected with the energy branch responsible for the heat production in complex buildings is to be seen in Fig. 3.

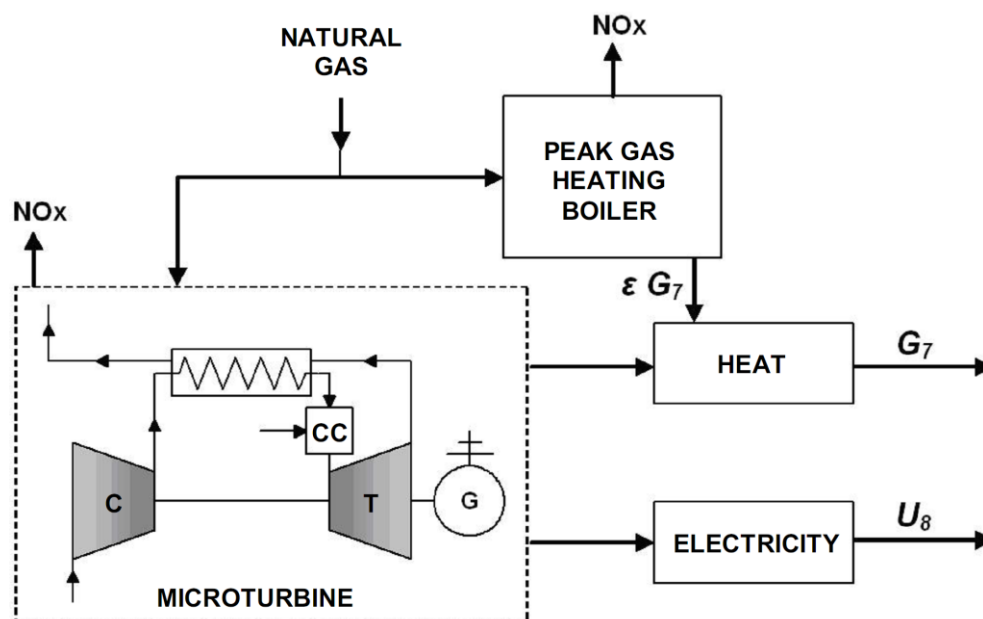


Fig. 3. Flow chart of the direct NOx emission in the energy branch which is responsible for the production of heat ($j=7$)

Set of balance equations of the cumulative emission of Nox concerning the considered case:

$$\begin{aligned}
a_{8,1}p_{8G}^* &= p_{1G}^* \\
a_{7,2}p_{7G}^* + a_{8,2}p_{8G}^* &= p_{2G}^* \\
a_{7,3}p_{7G}^* + a_{8,3}p_{8G}^* + a_{10,3}p_{10G}^* &= p_{3G}^* \\
a_{7,4}p_{7G}^* + a_{8,4}p_{8G}^* &= p_{4G}^* \\
a_{1,5}p_{1G}^* + a_{2,5}p_{2G}^* + a_{8,5}p_{8G}^* &= p_{5G}^* \\
a_{8,6}p_{8G}^* &= p_{6G}^* \\
\frac{P_{b7}}{G_7} + a_{9,7}p_{9D}^* &= p_{7G}^* + \frac{U_{87}}{G_7}p_{delg}^* \\
p_{8G}^* &= \frac{U_8 p_{delg}^* + D_8 p_{dels}^*}{U_{87} + D_8} \\
p_{9D}^* &= 0 \\
p_{10D}^* &= 0,003936
\end{aligned} \tag{8}$$

where a_{ij} – coefficients of the direct consumption of energy carriers, p_i^* – coefficient of the cumulative emission for energy carriers in the building, P_{b7} – annual direct Nox emission in the 7-th energy branch, G_7 – heat production, U_{87} – electricity by-production, D_8 – electricity supply from an external power system.

The coefficients of Nox cumulative emissions concerning each energy carrier are gathered in Table 3. Table 4 and Fig. 4 shows the cumulative NOx emissions charging following rooms in the building.

Table.3. Coefficients of NOx cumulative emissions concerning each energy carrier considered in the analysis

No	Energy carrier	Unit	NOx
1	Cooling medium 6/12 °C	kg/GJ	0,1578
2	Hot process water 85/45 °C	kg/GJ	0,008403
3	Hot tap water	kg/Mg	0,005216
4	Hot process water 60/45 °C	kg/GJ	0,002091
5	Air from the air conditioning unit	kg/Mg	0,001408
6	Ventilation air	kg/Mg	0,0002891
7	Heat for the heating system	kg/GJ	0,0005652
8	Electricity	kg/GJ	0,3248
9	Natural gas	kg/Mg	0
10	Drinking water	kg/Mg	0,003936

Table.4. Annual NOx cumulative emissions generated by the consumer subsystem (kg NOx/year)

No	Energy carrier	Office rooms	Auxiliary rooms	Garages	Monitoring and control
1	Cooling medium 6/12 °C	167,04	0,00	0,00	0,00
2	Hot process water 85/45 °C	0,00	7,16	0,00	0,00
3	Hot tap water	0,00	5,19	0,00	0,00

4	Hot process water 60/45 °C	3,51	0,00	0,00	0,00
5	Air from the air conditioning unit	64,13	42,75	0,00	0,00
6	Ventilation air	0,00	0,00	125,93	0,00
7	Heat for the heating system	0,00	0,00	0,00	0,00
8	Electricity	857,22	25,73	129,05	80,13
9	Natural gas	0,00	0,00	0,00	0,00
10	Drinking water	0,00	39,69	0,00	0,00
	Overall	1091,90	120,52	254,98	80,13

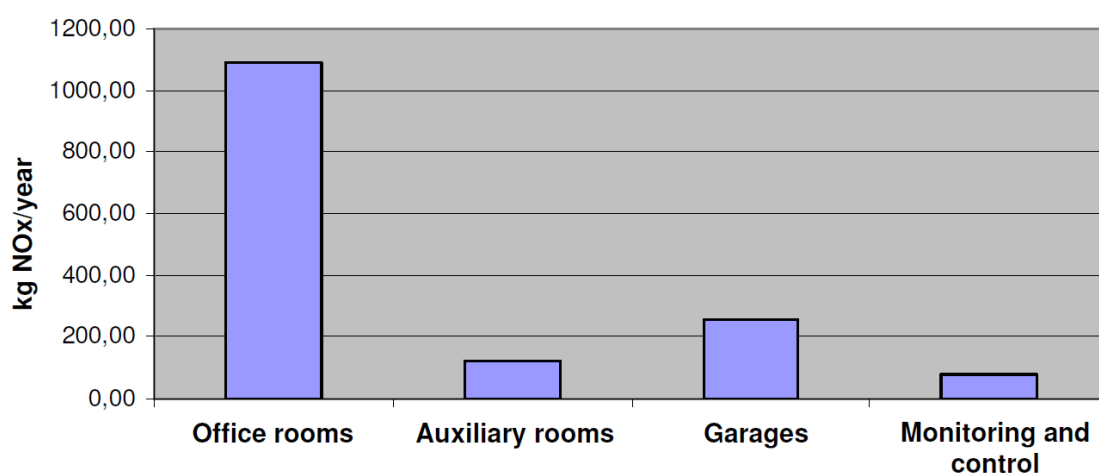


Fig. 4. Annual NOx cumulative emissions generated by the consumer subsystem of the considered office building

5. Conclusions

The paper deals with the application of the theory of interbranch flows („input-output analysis”) for the evaluation of cumulative emissions of noxious substances to the environment, generated by complex buildings. An analysis of the direct emissions is not a sufficient tool for ecological investigations, because most energy processes in modern complex buildings are interdependent. Studies have shown that on the basis of the annual energy balance a mathematical model of the balance of cumulative emissions for a complex building can be formulated and the coefficients of cumulative emissions concerning all energy carriers in the building may be calculated. In this paper this approach has been used to analyze cumulative NOx emissions generated by an exemplary office building.

The analysis of this building has shown that the most cumulative emissions result from the demand for electricity (Table 3). Office rooms (with an air-conditioning system, fan coil units, equipment and controls) are the main electricity consumers in the analyzed building and are responsible for most NOx cumulative emissions (70%) (Fig. 4). There is a great potential of improving the energy consumption in offices, for example by applying low-energy cooling methods. The presented method can be used in the designing of new and modernized complex buildings.

Acknowledgments

This paper was sponsored by the Polish Government-Grant „Integrated system of the operating energy-consumption reduction of buildings”.

The authors wish to express their gratitude to the Polish National Centre for Research and Development.

Nomenclature

- $\mathbf{A}, \overline{\mathbf{A}}$ – matrices of the coefficients of the consumption of energy carriers in energy and technological subsystem of analyzed building,
- $a_{ij}, \overline{a_{ik}}$ – coefficients of the consumption of the i -th energy carrier,
- $\mathbf{D}$ – vector of external energy supplies,
- $\mathbf{E}$ – unitary matrix,
- $\mathbf{F}, \overline{\mathbf{F}}$ – matrices of coefficients of the by-production of energy carriers,
- $f_{ij}, \overline{f_{ik}}$ – coefficients of the by-production of the i -th energy carrier,
- $\mathbf{G}$ – vector of the main production of energy carriers,
- G_i, G_j – main production of the j -th energy carrier and j -th energy branch,
- $\overline{\mathbf{G}}$ – vector of the production by technological branches,
- $\overline{G_k}$ – production of the given technological branch,
- i – consecutive number of energy carrier,
- m – number of all energy carriers in analyzed building (sum of all energy carriers in energy and consumers subsystems),
- n – number of all energy carriers in energy subsystem of analyzed building,
- p_{ki}^* – cumulative emission of the k -th kind concerning the i -th energy carrier,
- $\mathbf{P}_k^*$ – vector of average-weighted coefficients of the k -th kind cumulative emissions,
- p_{kDDi}^* – cumulative emission of the k -th kind concerning the i -th external supply of energy carriers,
- $\mathbf{P}_{kDG}^*$ – vector of the coefficients of the k -th kind cumulative emissions charging the external supplies of energy carriers.
- p_{kGj} – direct emission of the k -th kind occurring in the processes belong to the j -th energy branch,
- $\mathbf{P}_{kG}^*$ – vector of the coefficients of the k -th kind cumulative emissions charging the main production of energy carriers,
- p_{kui}^* – cumulative emission of k -th kind charging the i -th by-product calculated basing on substitution effect of main product.
- $\mathbf{P}_{ku}^*$ – vector of the coefficients of k -th kind cumulative emissions charging the by-production of energy carriers,
- $\mathbf{U}, \overline{\mathbf{U}}$ – by-production of energy carriers in the energy branch or technological branch,
- $\mathbf{Z}, \overline{\mathbf{Z}}$ – consumption of energy carriers in the energy branch or technological branch.

Subscripts

- i – i -th energy carrier,
- j – j -th energy branch,
- k – k -th technological branch,.

Accent above symbol (e.g. $\overline{a_{ik}}$, $\overline{f_{ik}}$) concerns flows of energy carriers in the subsystem of consumers (technological branch) in analyzed building.

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Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej

Celem przeprowadzanych badań w Etapie 8 jest opracowanie oraz aplikacja modelu matematycznego służącego do analizy systemowej gospodarki energetycznej kompleksu budowlanego użyteczności publicznej. W pierwszej kolejności dokonano przeglądu bazy wiedzy dotyczącej współczesnych urządzeń i systemów energetycznych stosowanych w kompleksach budowlanych użyteczności publicznej. Szczegółnej analizie poddano rozwiązania energetyczne wykorzystujące odnawialne źródła energii. Skompletowano bazę wiedzy o ich wskaźnikach energetycznych i ekologicznych. Następnie bazując na teorii przepływów międzygałęziowych opracowano modele matematyczne bilansu bezpośredniego oraz skumulowanego zużycia energii. Bazując na opracowanej metodyce stworzono model matematyczny skumulowanej emisji substancji szkodliwych do otoczenie. W modelach matematycznych uwzględniono możliwość wykorzystania nośników energii ze źródeł odnawialnych.

1. Opracowanie bazy wiedzy na temat urządzeń energetycznych wytwarzania ciepła, elektryczności i chłodu w budynkach użyteczności publicznej oraz możliwości zastosowania w nich odnawialnych źródeł energii.

Współczesne budynki użyteczności publicznej charakteryzują się szczególnie złożoną strukturą gospodarki energetycznej. Spowodowane to jest coraz powszechniejszym zastosowaniem różnego rodzaju wariantów instalacji ogrzewania, chłodzenia, wentylacji i klimatyzacji, a w przypadku kogeneracji również zasilania w energię elektryczną. Stwarza to określone możliwości wykorzystania odnawialnych źródeł energii w tego typu budynkach. Coraz częściej stosowane są układy realizujące gospodarkę skojarzoną polegającą na równoczesnym wytwarzaniu ciepła i elektryczności. Są to zarówno tradycyjne układy silnikowe tłokowe lub turbinowe, jak również układy skojarzone oparte na ogniwach paliwowych. W ostatnich latach dużą uwagę przywiązuje się do układów kogeneracyjnych wykorzystujących silniki Stirlinga. Układy takie mogą być zasilane biomasą spalaną bezpośrednio bądź uprzednio poddaną zgazowaniu. W tego typu układach z powodzeniem mogą zostać zastosowane również inne paliwa odnawialne np. biogaz czy płynne paliwa pochodzenia roślinnego. Pewne możliwości wykorzystania odnawialnych źródeł energii w budynkach użyteczności publicznej stwarza również technologia ORC (Organic Rankine Cycle). Przez zintegrowanie układów skojarzonych ciepłno elektrycznych z urządzeniami ziębniczymi możliwe jest równoczesne wytwarzanie ciepła, elektryczności i chłodu w jednym układzie. Są to tzw. układy „trigeneration”. W ramach przeprowadzonych badań stworzono bazę wiedzy na temat urządzeń energetycznych wytwarzania ciepła, elektryczności i chłodu w budynkach użyteczności publicznej oraz możliwości zastosowania w nich odnawialnych źródeł energii.

2. Model matematyczny bilansu bezpośredniego zużycia energii w gospodarce energetycznej kompleksu budowlanego

Z zebranych na potrzeby bazy wiedzy informacji o nowoczesnych systemach energetycznych w budynkach użyteczności publicznej wynika, że występuje potrzeba opracowania metodyki systemowej analizy gospodarki energetycznej dla tego typu obiektów. Metodyki, która będzie mogła być wykorzystana zarówno do analizy energetyczno ekologicznej eksploatacji budynków jak również do wspomagania projektowania ich optymalnego wariantu struktury gospodarki energetycznej. Model matematyczny bezpośredniego zużycia energii w gospodarce energetycznej budynku użyteczności publicznej został zbudowany w oparciu o teorię przepływów międzygałęziowych, co umożliwia analizę nie tylko bezpośredniego, ale również pośredniego zużycia nośników energii wynikającego z powiązań międzygałęziowych występujących w rozpatrywanym systemie. Opracowany model bilansu bezpośredniego zużycia energii w kompleksie budowlanym dotyczy bilansowania długoterminowego. W tablicy 1 przedstawiono strukturę przepływów międzygałęziowych w kompleksie budowlanym.

Tablica 1. Tablica przepływów międzygałęziowych

Nośnik energii	Część przychodowa				Część rozchodowa	
	Produkcja główna	Produkcja uboczna		Dostawa zewnętrzna	Przepływy międzygałęziowe	
		Podsystem energetyczny	Podsystem odbiorców		Podsystem energetyczny	Podsystem odbiorców
1	...	...	...	...	...	...
...	...	...	...	...	...	...
i	G_i	$\sum_{j=1}^n U_{ij}$	$\sum_{k=1}^p \bar{U}_{ik}$	D_{Gi}	$\sum_{j=1}^n Z_{ij}^G$	$\sum_{k=1}^p \bar{Z}_{ik}^G$
...	...	...	...	...	...	...
n	...	...	...	...	...	...
n+1	...	...	...	...	...	...
...	...	...	...	...	...	...
i	0	0	0	D_{Di}	$\sum_{j=1}^n Z_{ij}^D$	$\sum_{k=1}^p \bar{Z}_{ik}^D$
...	...	...	...	...	...	...
m	...	...	...	...	...	...

W zapisie macierzowym układ równań bilansowych bezpośredniego zużycia energii w kompleksie budowlanym użyteczności publicznej oraz nośników energii stanowiących dostawę zewnętrzną (przede wszystkim paliwa) ma postać:

$$\mathbf{G} + \mathbf{F}\mathbf{G} + \bar{\mathbf{F}}\bar{\mathbf{G}} + \mathbf{D}_G = \mathbf{A}_G\mathbf{G} + \bar{\mathbf{A}}_G\bar{\mathbf{G}}$$

$$\mathbf{D}_D = \mathbf{A}_D\mathbf{G} + \bar{\mathbf{A}}_D\bar{\mathbf{G}}$$

gdzie:



- $\mathbf{A}_G, \overline{\mathbf{A}}_G$ - macierze wskaźników jednostkowego bezpośredniego zużycia nośników energii w podsystemie energetycznym i w podsystemie odbiorców,
- $\mathbf{D}_G$ - wektor dostaw uzupełniających nośników energii wytworzonych w podsystemie energetycznym,
- $\mathbf{F}, \overline{\mathbf{F}}$ - macierze współczynników ubocznego wytwarzania nośników energii w podsystemie energetycznym i w podsystemie odbiorców,
- $\mathbf{G}, \overline{\mathbf{G}}$ - wektory produkcji głównej nośników energii w gałęziach energetycznych, bądź w gałęziach technologicznych,
- $\mathbf{D}_D$ - wektor dostaw nośników energii stanowiących dostawy zewnętrzne.
- $\mathbf{A}_D, \overline{\mathbf{A}}_D$ - macierze wskaźników jednostkowego bezpośredniego zużycia nośników energii stanowiących dostawy wyłączone odpowiednio w podsystemie energetycznym i w podsystemie odbiorców energii.

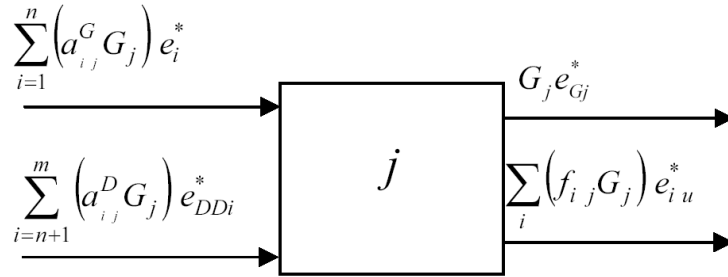
Analiza bezpośredniego zużycia energii nie obejmuje całkowitej energii jaka jest potrzebna do wytworzenia danego użytecznego nośnika energii (produktu) w kompleksie budowlanym. Stosowane bowiem do jego wytworzenia inne nośniki energii (np. paliwa) również wymagają pewnego zużycia energii w pośrednich procesach wytwórczych i transportowych. Zasilanie budynku ze źródeł odnawialnych również wiąże się z pewnym nakładem energetycznym. Tak więc każdy produkt (nośnik energii) jest wytwarzany w wyniku nie tylko bezpośredniego, ale i pośredniego zużycia energii w licznych ogniach poprzedzających w sieci powiązań energetycznych i technologicznych. Dlatego też kompletna analiza energetyczna powinna być oparta o rachunek skumulowanego zużycia energii.

3. Model matematyczny bilansu skumulowanego zużycia energii

Metodologia obliczania wskaźników skumulowanego zużycia energii dla nośników energii w kompleksie budowlanym jest oparta o opisany w punkcie 2 model matematyczny bilansu gospodarki energetycznej. Dane wejściowe do takiej analizy stanowią wyniki obliczeń bilansu bezpośredniego zużycia energii w kompleksie budowlanym oraz wskaźniki skumulowanego zużycia energii dla nośników energii dostarczanych z zewnątrz (wartości średnich wskaźników skumulowanego zużycia energii w krajowym systemie energetycznym).

W celu określenia relacji opisujących wskaźniki skumulowanego zużycia energii sporządza się bilanse skumulowanego zużycia na wzór liniowego modelu matematycznego gospodarki energetycznej kompleksu budowlanego.

Nośniki energii zużywane w kompleksie budowlanym mogą być produktami głównymi lub produktami ubocznymi podsystemu energetycznego, bądź mogą być dostarczane z zewnątrz (np. paliwa). Dlatego należy operować pojęciem średnioważonego wskaźnika skumulowanego zużycia energii. Bilans skumulowanego zużycia energii dla j -tej gałęzi energetycznej został przedstawiony na rys. 1.



Rys. 1. Schemat bilansowy skumulowanego zużycia energii w j -tej gałęzi energetycznej

Na schemacie bilansowym skumulowanego zużycia energii poszczególne symbole oznaczają:

- e_{ij}^G - wskaźnik jednostkowego bezpośredniego zużycia i -tego nośnika energii w j -tej gałęzi,
- G_j - produkcja główna j -tej gałęzi,
- e_i^* - średnioważony wskaźnik skumulowanego zużycia energii,
- e_{Gj}^* - wskaźnik skumulowanego zużycia energii w gałęzi j dotyczący produktu głównego,
- f_{ij} - wskaźnik ubocznego wytwarzania i -tego nośnika w j -tej gałęzi,
- e_{iu}^* - wskaźnik skumulowanego zużycia energii w odniesieniu do produktów ubocznych,
- a_{ij}^D - wskaźnik jednostkowego bezpośredniego zużycia i -tej dostawy wyłącznej w j -tej gałęzi,
- e_{DDi}^* - wskaźnik skumulowanego zużycia energii wyłącznej dostawy zewnętrznej.

Elementy wektora $\mathbf{e}^*$ średnioważonych wskaźników skumulowanego zużycia energii są obliczane według relacji:

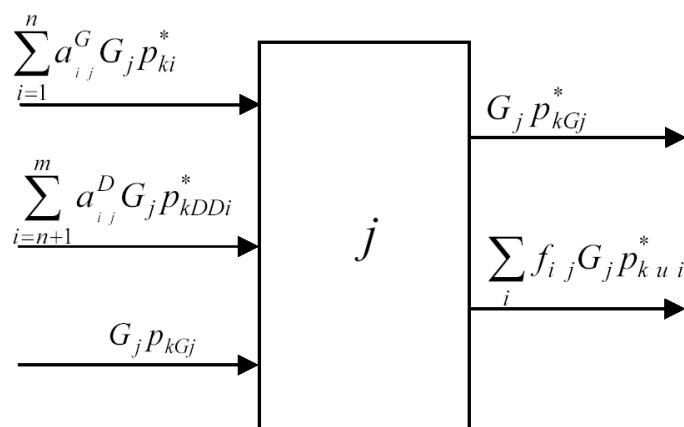
$$e_i^* = \frac{G_i e_{Gi}^* + \left(\sum_{j=1}^n (f_{ij} G_j) + \sum_{k=1}^p (\bar{f}_{ik} \bar{G}_k) \right) e_{iu}^* + D_{Gi} e_{DGi}^*}{G_i + \sum_{j=1}^n (f_{ij} G_j) + \sum_{k=1}^p (\bar{f}_{ik} \bar{G}_k) + D_{Gi}}$$

gdzie e_{DGi}^* oznacza wskaźnik skumulowanego zużycia energii dotyczący uzupełniającej dostawy zewnętrznej.

Tak więc wskaźniki skumulowanego zużycia energii nośników doprowadzanych do gałęzi „ j ” są w ogólnym przypadku wartością średnioważoną ze wskaźników skumulowanego zużycia energii produktu głównego, produktu ubocznego i uzupełniającej dostawy zewnętrznej. Wielkościami wejściowymi (zadanymi) w algorytmie analizy skumulowanego zużycia energii są wskaźniki skumulowanego zużycia energii dostaw zewnętrznych (uzupełniających i wyłącznych) do kompleksu budowlanego (głównie paliwa i energia elektryczna). Wskaźniki skumulowanego zużycia energii dla produktów ubocznych są określone zgodnie z zasadą unikniętych nakładów energetycznych bazując na wskaźniku skumulowanego zużycia energii produktu jednocelowego procesu zastąpionego przez wytwarzanie produktu ubocznego.

4. Wskaźniki skumulowanej emisji szkodliwych substancji

Produkcja nośników energii w budynku użyteczności publicznej jest nieodłącznie związana z emisją szkodliwych gazów, cieczy i stałych produktów odpadowych. Bezpośrednie zużycie nośników energii (głównie paliw) prowadzi do bezpośredniej emisji związanej z produkcją danego nośnika energii. Ale nośniki te dostarczone do kompleksu budowlanego są już obciążone szkodliwymi emisjami wynikającymi z wcześniejszych etapów produkcji i procesów transportowych. Jest to, podobnie jak w przypadku analizy skumulowanego zużycia energii, rezultatem istnienia energetyczno technologicznej sieci wzajemnych powiązań. Tak więc obciążenie ekologiczne danego nośnika energii zużywanego w kompleksie budowlanym zależy nie tylko od bezpośredniej emisji, ale także od emisji, która miała miejsce w procesach poprzedzających i w transporcie. Analogicznie więc tak jak w przypadku wskaźników skumulowanego zużycia energii należy posłużyć się wskaźnikami skumulowanej emisji. Na rys. 2 przedstawiono schemat bilansowy skumulowanej emisji k -tej substancji szkodliwej w j -tej gałęzi.



Rys. 2. Schemat bilansowy skumulowanej emisji

Na rys. 2 poszczególne symbole oznaczają:

p_{ki}^* - skumulowaną emisję k -tego rodzaju dotyczącą i -tego nośnika energii,

p_{kDDi}^* - skumulowaną emisję k -tego rodzaju dotyczącą i -tej dostawy zewnętrznej wyłącznej,

p_{kGj} - emisję bezpośrednią k -tego rodzaju powstającą w procesach należących do j -tej gałęzi,

p_{kui}^* - emisję skumulowaną k -tego rodzaju obciążającą i -ty produkt uboczny wyznaczaną w oparciu o efekt zastępowania produktu głównego przez produkt uboczny.

Średnioważony skumulowany wskaźnik emisji k -tego rodzaju obciążający i -ty produkt główny jest obliczany z relacji:

$$p_{ki}^* = \frac{G_i p_{kGi}^* + \left(\sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k \right) p_{kui}^* + D_{Gi} p_{kDGi}^*}{G_i + \sum_{j=1}^n f_{ij} G_j + \sum_{k=1}^p \bar{f}_{ik} \bar{G}_k + D_{Gi}}$$

gdzie p_{kDGi}^* oznacza wskaźnik skumulowanej emisji k -tego rodzaju dostawy uzupełniającej.

Wskaźniki skumulowanych emisji obciążających dostawy zewnętrzne nośników energii są a priori znane i wynikają z analizy dotyczącej sieci wzajemnych powiązań w skali kraju. Wskaźniki emisji dotyczące produktów ubocznych są wyznaczane w oparciu o metodę zastępowania, która bazuje na zasadzie unikniętych emisji.

5. Podsumowanie i informacje o dalszych badaniach

Zbiór modeli matematycznych bilansu bezpośredniego zużycia energii, bilansu skumulowanego zużycia energii, bilansu skumulowanej emisji substancji szkodliwych oraz bilansu kosztu termoeekologicznego stanowi komplementarnie ujętą metodykę analizy systemowej gospodarki energetycznej kompleksu budowlanego. Wspólną cechą tych modeli jest podejście oparte na teorii przepływów międzygałęziowych („input-output analysis”).

Przedstawione podejście jest wykorzystywane w dalszej części prac w Etapie nr 8 do sformułowania modelu matematycznego doboru struktury gospodarki energetycznej nowego lub modernizowanego budynku użyteczności publicznej w fazie projektu wstępnego.



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Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej

W niniejszej pracy zaprezentowano wyniki badań Etapu 8 strategicznego projektu badawczego dotyczącego zwiększenia wykorzystania energii z odnawialnych źródeł energii (OZE) w budownictwie. Etap 8 nosi tytuł „Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej”. Celem przeprowadzanych badań w tym etapie jest opracowanie modelu matematycznego służącego do analizy systemowej gospodarki energetycznej kompleksu budowlanego użyteczności publicznej. W ramach dotychczasowych prac skompletowano bazę wiedzy o urządzeniach i instalacjach energetycznych stosowanych w tego typu budynkach poddając szczególnej analizie rozwiązania wykorzystujące odnawialne źródła energii. Opracowano algorytmy i modele matematyczne bilansu bezpośredniego jak również skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz model bilansu kosztu termoeologicznego. W modelach matematycznych uwzględniono możliwość wykorzystania nośników energii ze źródeł odnawialnych. Efekty powyższych prac zostały zaprezentowane w materiałach konferencyjnych „I Seminarium zadania badawczego nr 3 strategicznego projektu badawczego - Zintegrowany system zmniejszenia eksploatacyjnej energochłonności budynków” [1]. W dalszej kolejności prace w Etapie 8 polegały na aplikacji opracowanych algorytmów i modeli do obliczeń testowych. Efektem obliczeń testowych są wskaźniki energetyczno-ekologiczne charakteryzujące oddziaływanie rozpatrywanego budynku na środowisko naturalne. Obliczenia przeprowadzono dla przykładowego budynku biurowego. Część tych badań została zamieszczona w artykule pt. “Mathematical model for the simulation of cumulative emissions generated by energy management of complex buildings” i zostanie zaprezentowana na konferencji naukowej ECOS 2011 - The 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems organizowanej w Serbii w dniach 4-7 lipca 2011.

Zastosowanie modelu matematycznego bilansu gospodarki energetycznej kompleksu budowlanego do wyznaczania wskaźników energetyczno-ekologicznych w kompleksach budowlanych – obliczenia testowe

Model matematyczny bilansu gospodarki energetycznej rozpatrywanego kompleksu budowlanego został sformułowany na podstawie ogólnej metodologii zaprezentowanej na ostatnim seminarium Projektu [1]. Wykorzystując utworzone modele matematyczne bilansu bezpośredniego i skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz model bilansu

kosztu termoeologicznego wykonano obliczenia testowe dla przykładowego budynku. Analizowanym kompleksem budowlanym był typowy biurowiec, który został ukończony w 1999 roku. Powierzchnia użytkowa budynku wynosi 8000m². Eksploatacja budynku wymaga dostarczania następujących nośników energii: ciepła (dostawa z sieci ciepłowniczej), elektryczności (z sieci elektroenergetycznej), gazu ziemnego oraz wody wodociągowej.

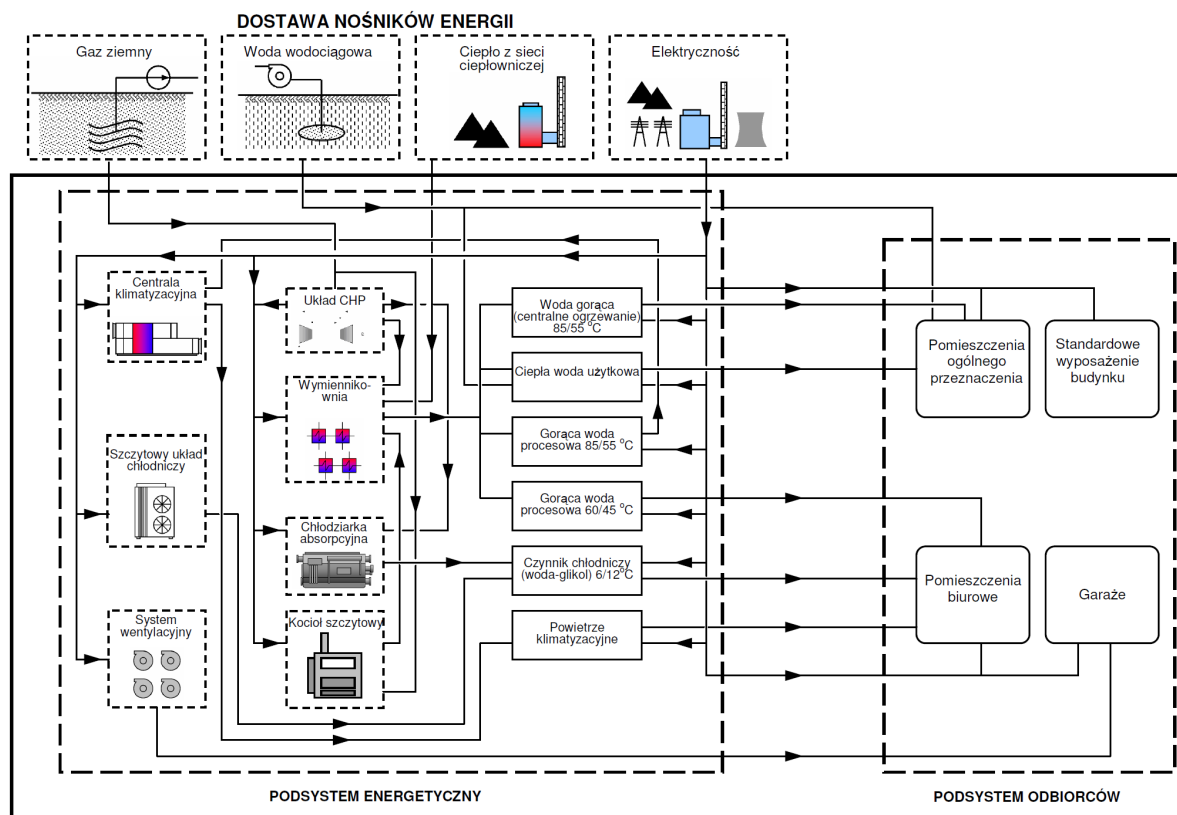
W podsystemie energetycznym budynku wytwarzane są następujące nośniki energii:

- czynnik chłodzący (woda-glikol) 6/12°C,
- gorąca woda procesowa (na cele centralnego ogrzewania oraz centrali klimatyzacyjnej) 85/55 °C,
- ciepła woda użytkowa,
- ciepła woda procesowa 60/45 °C (na cele klimatyzatorów),
- powietrze klimatyzacyjne.

Podsystem odbiorców nośników energii obejmuje:

- pomieszczenia biurowe wyposażone w klimatyzatory,
- pomieszczenia ogólnego przeznaczenia z centralnym systemem ogrzewania,
- standardowe wyposażenie budynku, takie jak: monitoring, systemy bezpieczeństwa, oświetlenie zewnętrzne, itp.
- przestrzeń parkingowe z mechaniczną wentylacją wyciągową.

Realizacja gospodarki energetycznej przykładowego budynku była analizowana w różnych wariantach struktury. Przykładowy wariant struktury gospodarki energetycznej (z wykorzystaniem układu CHP bazującym na mikroturbinie gazowej) pokazano na rysunku 1.



Rys. 1. Schemat powiązań międzygałęziowych w gospodarce energetycznej przykładowego budynku – wariant z układem CHP bazującym na mikroturbinie gazowej



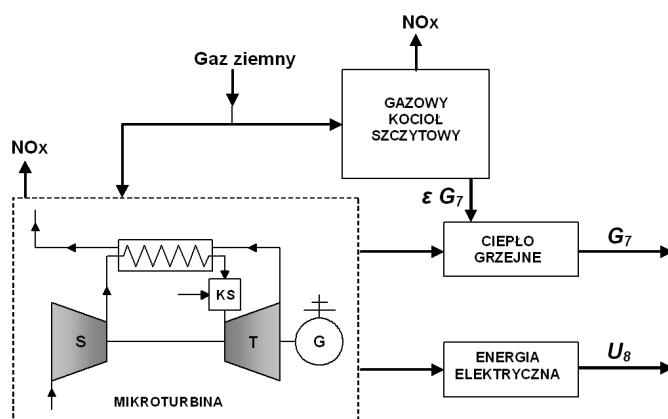
Analiza skumulowanej emisji szkodliwych substancji

Przykładowy bilans skumulowanej emisji substancji szkodliwych został przeprowadzony dla wariantu gospodarki energetycznej rozpatrywanego kompleksu budowlanego z zastosowaniem układu CHP, bazującym na mikroturbinie gazowej. Analizę oparto na przedstawionym w [1] modelu matematycznym obliczania wskaźników skumulowanej emisji substancji szkodliwych. W analizowanym przykładzie obliczeniowym rozpatrzono emisję związków NO_x. Dane wejściowe do tej procedury stanowią wyniki rocznego bilansu bezpośredniego zużycia energii w analizowanym kompleksie budowlanym, wskaźniki skumulowanej emisji obciążające nośniki energii dostarczane do budynku z zewnątrz oraz wielkości emisji bezpośrednich powstające w procesach należących do poszczególnych gałęzi energetycznych i technologicznych. W analizie uwzględniono efekt zastępowania przez energię elektryczną produkowaną w układzie CHP energii elektrycznej wytwarzanej z tego samego paliwa w elektrowni gazowej. Uwzględniono sprawność transformacji i przesyłania energii elektrycznej do budynku. Wybrane dane wejściowe do analizy zestawiono w tablicy 1. W analizie pominięto emisję związaną z wydobywaniem i dostarczaniem gazu ziemnego do budynku. Na podstawie analizy procesowej określono wskaźniki bezpośredniej emisji w gałęziach gospodarki energetycznej budynku. Bezpośrednia emisja substancji szkodliwych w podsystemie energetycznym analizowanego kompleksu budowlanego ma miejsce w układzie skojarzonym ciepłno-elektrycznym oraz w gazowym kotle szczytowym. Schemat bilansu bezpośredniej emisji NO_x związanej z gałęzią energetyczną odpowiedzialną za produkcję ciepła w rozpatrywanym przykładzie przedstawiono na rys. 2.

Tablica 1. Wybrane dane wejściowe do analizy skumulowanej emisji zanieczyszczeń dla analizowanego budynku

Wskaźnik skumulowanej emisji NO _x dla energii elektrycznej wytwarzanej w elektrowni gazowej	$p_{d\,el\,g}^* = 0,136 \text{ (kg/GJ}_{el}\text{)}$
Wskaźnik skumulowanej emisji NO _x dla energii elektrycznej wytwarzanej w elektrowni systemowej	$p_{d\,el\,s}^* = 0,4861 \text{ (kg/GJ}_{el}\text{)}$
Wskaźnik skumulowanej emisji NO _x dla pozyskania i dostarczenia do budynku wody wodociągowej	$p_{d\,w}^* = 0,003936 \text{ (kg/Mg)}$
Wskaźnik bezpośredniej emisji NO _x dla układu CHP	$p_{b\,CHP} = 0,0884 \text{ kg/GJ}_c$
Wskaźnik bezpośredniej emisji NO _x dla gazowego kotła szczytowego	$p_{b\,k\,sz} = 0,005556 \text{ kg/GJ}_c$
Roczna produkcja ciepła w układzie CHP	$Q_{CHP} = 3308 \text{ GJ/rok}$
Roczna produkcja ciepła szczytowego w budynku	$Q_{k\,sz} = 367,6 \text{ GJ/rok}$
Roczna uboczna wytwórczość energii elektrycznej w układzie CHP	$U_g = 2150 \text{ GJ/rok}$
Zapotrzebowanie na ciepło dla budynku	$Q = 3675,66 \text{ GJ/rok}$
Sprawność energetyczna układu CHP	$\eta_{E\,CHP} = 0,77$
Sprawność energetyczna gazowego kotła szczytowego	$\eta_{E\,k\,sz} = 0,85$

W rozważanym przypadku ma miejsce uboczne wytwarzanie energii elektrycznej w układzie CHP. Założono, że ciepło jest produktem głównym. Dlatego też, obciążenie ciepła emisjami substancji szkodliwych powinno być pomniejszone o emisję związaną z zastąpieniem produkcji elektryczności dostawą z systemu elektroenergetycznego.



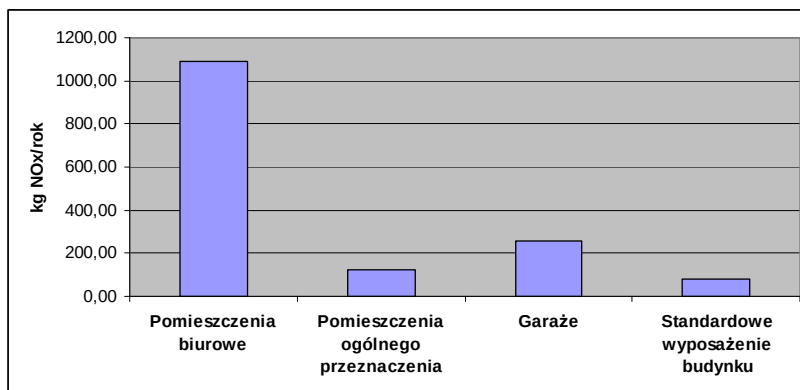
Rys.2. Przykład schematu bilansu bezpośredniej emisji NO_x w gałęzi energetycznej budynku odpowiedzialnej za produkcję ciepła ($j=7$), G_7 – roczna produkcja ciepła, U_8 – roczna uboczna produkcja elektryczności

Wskaźniki skumulowanej emisji dla poszczególnych nośników energii zebrano w tablicy 2.

Tablica 2. Wskaźniki skumulowanej emisji związków NO_x dla nośników energii w analizowanym kompleksie budowlanym

lp.	Nośnik energii	JED.	NO _x
1	Czynnik chłodzący 6/12 °C	kg/GJ	0,1578
2	Gorąca woda procesowa 85/45 °C	kg/GJ	0,008403
3	CWU	kg/Mg	0,005216
4	Gorąca woda procesowa 60/45 °C	kg/GJ	0,002091
5	Powietrze z centrali klimatyzacyjnej	kg/Mg	0,001408
6	Powietrze wentylacyjne	kg/Mg	0,0002891
7	Ciepło grzejne	kg/GJ	0,0005652
8	Energia elektryczna	kg/GJ	0,3248
9	Gaz ziemny	kg/Mg	0
10	Woda wodociągowa	kg/Mg	0,003936

Na rys. 3 zebrano roczne wielkości obciążenia emisjami NO_x dla wszystkich odbiorców w analizowanym budynku.



Rys. 3. Roczne emisje NO_x obciążające podsystem odbiorców analizowanego budynku



Wykonane obliczenia wykazały, że w rozpatrywanym budynku największą emisją NO_x obciążona jest energia elektryczna. Pomieszczenia biurowe odpowiadają za blisko 70% skumulowanej emisji NO_x, a jest to spowodowane zastosowaniem urządzeń i instalacji zużywających znaczne ilości elektryczności. Świadczy to o istnieniu dużego potencjału poprawy zużycia energii, a tym samym ograniczenia skumulowanej emisji w tego rodzaju pomieszczeniach poprzez np. zastosowanie niskoenergetycznych (niskoenergetycznych) metod chłodzenia i ogrzewania budynku.

Oprócz analizy skumulowanej emisji substancji szkodliwych wykonano również obliczenia dla przykładowego budynku w zakresie analizy skumulowanego zużycia energii oraz oceny kosztu termoeekologicznego. Przeprowadzone obliczenia testowe wykazują dużą przydatność sformułowanych na wcześniejszym etapie pracy algorytmów i modeli do systemowej analizy kompleksów budowlanych. Utworzone modele matematyczne charakteryzują się uniwersalnością zastosowania. Wygenerowany model wariantu gospodarki energetycznej budynku może zostać z łatwością zmodyfikowany pod względem zastosowania różnych rozwiązań energetycznych (w tym wykorzystujących odnawialne źródła energii).

Przeprowadzone obliczenia testowe wykazują, iż oddziaływanie kompleksu budowlanego na środowisko naturalne jest ściśle uzależnione od rodzaju zastosowanych w nim urządzeń i instalacji energetycznych. Dlatego też, celowym jest opracowanie algorytmu do automatyzacji doboru struktury gospodarki energetycznej kompleksu budowlanego w aspekcie wymaganych potrzeb energetycznych oraz obranej funkcji celu. Prace nad tego rodzaju algorytmem będą kontynuowane w ramach dalszych badań w Etapie 8 projektu.

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- [1]. Ziębik A., Hoinka K.: Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej. Materiały konferencyjne „I Seminarium zadania badawczego nr 3 strategicznego projektu badawczego - Zintegrowany system zmniejszenia eksploatacyjnej energochłonności budynków”, Gliwice, 10 grudnia 2010.
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Analiza systemowa gospodarki energetycznej kompleksu budowlanego użyteczności publicznej

Badania przeprowadzane w etapie nr 8 miały na celu opracowanie modeli matematycznych służących do analizy systemowej gospodarki energetycznej kompleksu budowlanego użyteczności publicznej. Dotychczasowe prace polegały na opracowaniu algorytmów i modeli bilansu bezpośredniego, jak również skumulowanego zużycia energii, skumulowanej emisji substancji szkodliwych oraz model bilansu kosztu termoeologicznego. W modelowaniu uwzględniono możliwość wykorzystania nośników energii ze źródeł odnawialnych. Przeprowadzono obliczenia testowe na przykładzie budynku biurowego. Algorytmy obliczeniowe tych analiz zostały zamieszczone w materiałach konferencyjnych Pierwszego [6], natomiast wyniki obliczeń testowych w materiałach Drugiego [7] *"Seminarium zadania badawczego nr 3 strategicznego projektu badawczego - Zintegrowany system zmniejszenia eksploatacyjnej energochłonności budynków"*. Wyniki badań przedstawiono również w referacie pt. *"Mathematical model for the simulation of cumulative emissions generated by energy management of complex buildings"* na międzynarodowej konferencji ECOS 2011 zorganizowanej w Serbii [1]. Ostatnie badania zostały również zaprezentowane w artykule dla czasopisma Energy and Buildings, który aktualnie podlega recenzji. Część prac poświęcono opracowaniu modułu zautomatyzowanych algorytmów odpowiedzialnych za utworzenie wariantów sieci powiązań energetycznych i technologicznych w budynku użyteczności publicznej. Celem tych prac było opracowanie procedury doboru struktury gospodarki energetycznej w kompleksie budowlanym. Procedurę tą rozszerzono o metodą dekompozycji globalnego zadania optymalizacyjnego, której algorytm zamieszczono w niniejszej pracy. Wyniki powyższych prac zostały zamieszczone w IX rozdziale przygotowywanej publikacji książkowej dla wydawnictwa Springer pt.: *"Energy systems of complex buildings"* autorstwa A. Ziębik i K. Hoinka.

1. Dobór optymalnej struktury gospodarki energetycznej kompleksu budowlanego metodą dekompozycji globalnego zadania optymalizacyjnego

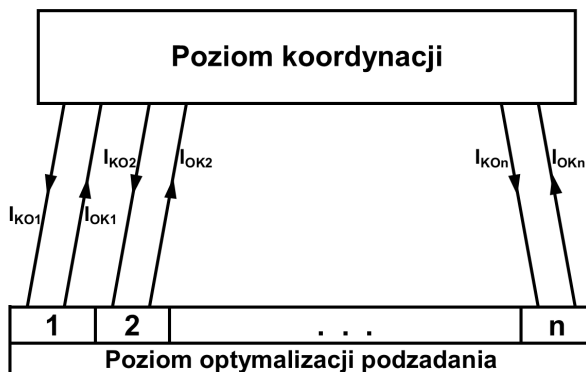
1.1. Zagadnienie dekompozycji

Metoda dekompozycji polega na podziale globalnego zadania optymalizacyjnego na szereg podzadań rozwiązywanych niezależnie (autonomicznie), a następnie podlegających koordynacji. Dla dekompozycji istotny jest stopień spójności systemu. Od niego bowiem zależy wielkość zadania koordynacyjnego. W metodzie dekompozycji wykorzystuje się cechę hierarchiczności charakterystyczna dla dużych systemów energetycznych, do których należy gospodarka energetyczna kompleksu budowlanego. Zagadnienie dekompozycji jest związane z następującymi problemami:

- wydzielenie oddzielnych podzadań,

- sformułowanie algorytmów optymalizacyjnych poszczególnych podzadań w postaci dogodnej do koordynacji,
- zbudowanie procedury koordynacyjnej.

Na Rys.1 przedstawiono ideę metody dekompozycji globalnego zadania optymalizacyjnego.



Rys.1. Idea metody dekompozycji globalnego zadania optymalizacyjnego

Aby autonomiczne kryteria optymalizacyjne na dowolnym poziomie hierarchii były zgodne z kryterium globalnym, z poziomu koordynacji jest przekazywany zbiór informacji $\{I_{KO1}, I_{KO1}, \dots, I_{KOn}\}$ na poziom optymalizacji autonomicznej poszczególnych podzadań. Po przeprowadzeniu autonomicznej optymalizacji dla każdego podsystemu przesyłany jest na górny poziom hierarchii zbiór informacji $\{I_{OK1}, I_{OK1}, \dots, I_{OKn}\}$ stanowiącej wynik autonomicznej optymalizacji. Na górnym poziomie hierarchii rozpoczyna się wówczas kolejna iteracja, której rezultatem jest poprawiony zbiór parametrów $\{I_{OKi}\}$ podlegający przesyłaniu na dolny poziom optymalizacji. Tak więc metoda dekompozycji jest procedurą iteracyjną. Dla każdego rozwiązania na górnym poziomie hierarchii jest wymagana korekta rozwiązań na dolnym poziomie i odwrotnie. Liczba iteracji zależy od stopnia szczegółowości modelu matematycznego, od dokładności informacji wejściowej i od dokładności metod optymalizacji. Jedną z najbardziej efektywnych metod dekompozycji jest metoda Lagrange'a [2].

1.2. Model matematyczny optymalizacyjny doboru struktury podsystemu energetycznego kompleksu budowlanego

Celem projektu wstępnego jest wybór optymalnego wariantu struktury gospodarki energetycznej kompleksu budowlanego. Pod wyborem struktury jest rozumiany dobór rodzaju i liczby maszyn oraz urządzeń energetycznych, jak również powiązań między nimi. Kryterium doboru optymalnej struktury gospodarki energetycznej stanowi żądanie maksymalizacji rocznego efektu ekonomicznego działania kompleksu budowlanego. Funkcją celu dla założonego zapotrzebowania podsystemu odbiorców na energię jest więc minimalizacja rocznego kosztu działania podsystemu energetycznego kompleksu budowlanego.

1.3. Dekompozycja globalnego zadania optymalizacyjnego

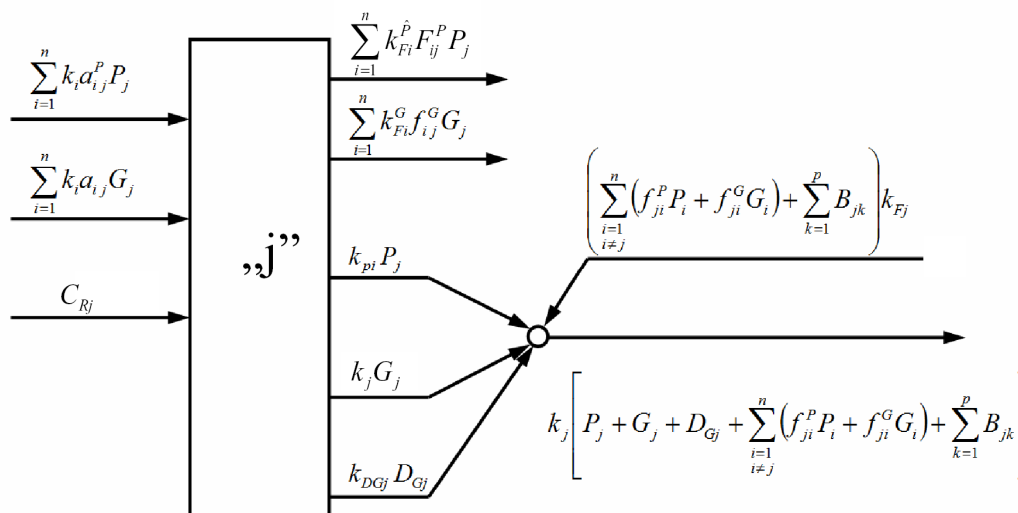
W celu rozwiązania globalnego zadania optymalizacyjnego (1.1) wymagana jest znajomość wykresu uporządkowanego zapotrzebowania na dany nośnik energii, jak również znajomość wskaźników zużycia i ubocznego wytwarzania nośników energii. Te ostatnie określane są na podstawie charakterystyk energetycznych zależnych zarówno od nieznanymi mocy i strumieni

nominalnych, jak również od zmiany obciążeń urządzeń i maszyn energetycznych. Zmiany obciążenia są przedstawione za pomocą wykresów uporządkowanych. Jednak do skonstruowania wykresu uporządkowanego potrzebna jest znajomość wskaźników zużycia lub ubocznego wytwarzania nośników energii. Tak więc, konstrukcja wykresów uporządkowanych zapotrzebowania na nośniki energii, określenie wskaźników jednostkowego zużycia lub ubocznego wytwarzania nośników energii, jak również dobór mocy nominalnych maszyn i urządzeń energetycznych oraz nominalnych strumieni dostaw zewnętrznych są zadaniami wzajemnie ze sobą powiązanymi. Ich rozwiązanie wymaga zastosowania dekompozycji globalnego zadania optymalizacyjnego [4]. W tym celu zastosowana zostanie metoda dekompozycji Lagrange'a [2] (Rys. 1).



Rys.1.4. Schemat dekompozycji za pomocą metody Lagrange'a

W celu określenia wektora wskaźników Lagrange'a wymagana jest znajomość procedury koordynacyjnej zapewniającej zgodność optimum lokalnego wymaganego na poziomie gałęzi energetycznej z optimum globalnym. Dla określenia tej procedury w rozpatrywanej analizie należy sformułować funkcję celu na poziomie j-tej gałęzi energetycznej. Na rys. 2. przedstawiono pomocniczy schemat obliczeniowy dla sformułowania gałęziowej funkcji celu i ustalenia dalszych rozważań. Produkcja główna i uboczna stanowią efekty użyteczne działania gałęzi energetycznej. Rozróżnia się koszty jednostkowe wytwarzania produkcji podstawowej i szczytowej oraz produkcji ubocznej danego nośnika energii. Uwzględnia się także dostawę uzupełniającą nośnika energii po koszcie jednostkowym narzuconym przez dostawcę. Dlatego w przypadku zasilania gałęzi energetycznej przez nośnik wytworzony w podsystemie energetycznym kompleksu budowlanego należy posłużyć się średnim kosztem jednostkowym pozyskania danego nośnika energii. Koszty dostaw zewnętrznych (uzupełniających i ubocznych) są ujęte w pozycji . W przypadku dostaw uzupełniających nakłady obok kosztów zakupu ujmują także koszty stałe i zmienne związane z przygotowaniem dostawy nośnika energii do użytkowania w kompleksie budowlanym (np. koszt eksploatacji węzła ciepłowniczego). Na rys. 2 przedstawiono również węzeł sumacyjny dla określenia średniego kosztu nośnika energii.



Rys. 2. Pomocniczy schemat dla sformułowania funkcji celu gałęzi energetycznej

Funkcja celu dotycząca j-tej gałęzi podsystemu energetycznego ma postać:

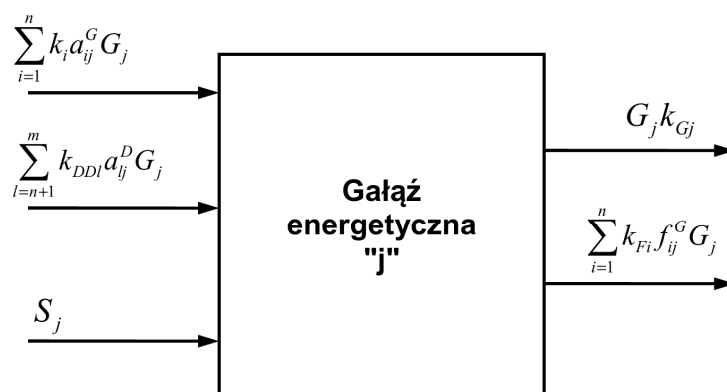
$$\phi = K_{Rj} + \sum_{i=1}^n k_i (a_{ij}^P P_j + a_{ij}^G G_j) - \sum_{i=1}^n k_{Fi} f_{ij}^P P_j - \sum_{i=1}^n k_{Fi} f_{ij}^G G_j \Rightarrow \min$$

W pierwszym przybliżeniu iteracyjnego algorytmu dekompozycji wektory $\mathbf{k}$ i $\mathbf{k}_f$ kosztów jednostkowych są zakładane. Zakładane są również te wskaźniki jednostkowego zużycia nośników energii, które mają charakter sprzężeń zwrotnych (tzn. znajdują się poniżej głównej przekątnej macierzy „input-output” powiązań międzygałęziowych). Po rozwiązaniu autonomicznych zadań optymalizacyjnych z uwzględnieniem lokalnych ograniczeń dla wszystkich gałęzi na niższym poziomie hierarchii następuje powrót na górny poziom hierarchii (poziom koordynacji), gdzie sporządzany jest skorygowany bilans energii i wyznaczany nowy wektor kosztów jednostkowych nośników energii według procedury koordynacyjnej. Skorygowany wektor kosztów jest przekazywany na dolny poziom hierarchii, gdzie następuje autonomiczna optymalizacja poszczególnych gałęzi energetycznych w kolejnej iteracji. Koniec iteracji wynika z założonej dokładności obliczeń kosztów jednostkowych nośników energii.

1.4. Metoda macierzowa obliczania kosztów jednostkowych nośników energii

Złożoność powiązań w gospodarce energetycznej, z których część ma charakter sprzężeń zwrotnych powoduje, że koszty jednostkowe nośników energii można wyznaczyć jedynie drogą kolejnych przybliżeń. Dlatego zastosowanie metody macierzowej obliczania kosztów jednostkowych nośników energii bazującej na modelu „input-output” bilansu energetycznego prowadzi do rozwiązania problemu. Warunkiem koniecznym zastosowania metody macierzowej obliczania kosztów jednostkowych nośników energii jest zamknięty bilans energii według wspomnianego modelu „input-output”.

Nośniki energii zużywane w kompleksie budowlanym mogą być wytwarzane jako produkty główne lub uboczne w podsystemie energetycznym lub mogą być dostarczane z zewnątrz. Dlatego rozróżnia się koszty jednostkowe podstawowej i szczytowej części produkcji głównej, koszty produkcji ubocznej i uzupełniających dostaw zewnętrznych [4]. W przypadku zużycia nośników energii należy posłużyć się średnioważonym kosztem jednostkowym uwzględniając dodatkowo koszty zmiany parametrów, transportu i dystrybucji.



Rys. 3. Bilans kosztów w przypadku produkcji szczytowej gałęzi „j”

Bilans kosztów dotyczący szczytowej części produkcji j-tej gałęzi energetycznej (Rys. 3) ma postać:

$$\sum_{i=1}^n k_i a_{ij}^G G_j + \sum_{l=n+1}^m k_{DDl} a_{lj}^{GD} G_j + S_j = G_j k_{Gj} + \sum_{i=1}^n k_{Fi} f_{ij}^G G_j$$

gdzie:

- k_i –średnioważony koszt jednostkowy i-tego nośnika energii,
- k_{DDl} –koszt jednostkowy l-tej dostawy wyłącznej,
- k_{Gj} –koszt jednostkowy szczytowej części produkcji j-tego nośnika energii,
- k_{Fi} –koszt jednostkowy i-tego nośnika energii produkowanego ubocznie,
- S_j –umowny koszt stały.

Człon S_j obejmuje wszystkie pozostałe składniki kosztu poza kosztami zużywanych nośników energii. Z uwagi na to, że S_j zawiera głównie koszty stałe, został on nazwany umownym kosztem stałym.

Koszty jednostkowe produktów ubocznych są określane na podstawie metody kosztów unikniętych [3]. Koszty jednostkowe dostaw zewnętrznych (uzupełniających i wyłącznych) są wielkościami zadanymi (ceny nośników energii obowiązujące w krajowym systemie energetycznym).

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ENERGY SYSTEMS OF COMPLEX BUILDINGS

2012

Foreword

Modern complex buildings, such as supermarkets, university campuses, airports, sports and recreation centres, are characterised by more and more complex energy management due to a growing share of distributed energy systems. Thus, energy carriers satisfying the needs of consumers in complex buildings (office rooms in office buildings, refrigerator counters in supermarkets and so on) are produced in a network of mutually connected energy processes, some of which are of feedback character. These are responsible for the necessity of applying the method of subsequent approximations when the balances of the respective energy carriers are set up separately. The systems approach of energy balancing, which is the basis of the energy analysis both in designing and exploitation, eliminates this disadvantage.

The systems approach applied in this book is generally based on Leontief's "input-output" analysis, supplemented by the characteristic features of energy management of an industrial or municipal system, for instance, the division of the main production of energy carriers into the basic and peak part, or including the by-products of some branches completing the main production of some other branch in the set of balances (e.g., heat from the recovered waste energy supplementing the production of heat in CHP plants). Input-output analysis, as quoted by Leontief, may be usefully applied both in the case of a very large economical system, such as the economy of a whole country, and a single enterprise such as complex buildings. This approach is in every case essentially the same.

This book comprises nine chapters. The first three chapters deal with some selected problems of systems analysis constituting the fundamentals of mathematical modelling of energy systems in complex buildings, both already existing ones and those to be constructed. Chapter 1 presents the idea of a system and its environment. The kinds and features of systems, as well as methods of describing them are presented. Chapter 2 is devoted to large energy systems, drawing the reader's attention to their hierarchical character, which may be applied in optimisation. The subject matter of Chapter 3 is the mathematical modelling of large energy systems. Special attention has been paid to input-output analysis and the method of decomposing the global optimisation task which makes use of the hierarchical structure of large energy systems.

Chapter 4 serves as an introduction to the application of systems analysis in mathematical modelling of the energy management of complex buildings. Typical complex buildings are described, as well as the ways of supplying them with energy carriers. Special attention is paid to distributed energy systems (particularly small-scale CHP units) and the

utilisation of renewable energy resources. Chapter 5 stresses the role of the municipal energy sector in the energy system of the country. The supply of heat to complex buildings via district heating networks and ways to control the supply of heat are presented. This chapter deals also with the fundamentals of the cogeneration of heat and electricity, and the idea of “trigeneration”, that is a CHP unit integrated with a cooling system. The index PES (Primary Energy Savings) has been analyzed concerning various techniques of cogeneration.

Chapter 6 and 7 are the fundamental part of the book dealing with the systems approach to complex buildings. Chapter 6 contains mathematical models of the balances of direct and cumulative energy consumption, the model of cumulative emissions of noxious substances, and a model of calculating the thermo-ecological costs. The application of the input-output model for systems analysis of rationalising the energy management of complex buildings is also presented in this chapter. Chapter 7 provides practical examples of applying previously mentioned models, viz., systems analysis of direct and cumulative energy consumption, and cumulative NO_x and CO₂ emissions, as well as calculations and analysis of the thermo-ecological costs. This chapter also contains examples of the application of input-output analysis, assessing the system effects of rationalisation of the energy management of complex buildings. A comprehensive example concerns the application of night cooling ventilation of rooms in the subsystem of consumers. Another example concerns the modernisation of the energy subsystem of complex buildings by means of applying a CHP unit. In both these cases system effects concern the decrease in the supply of energy carriers from outside, which are the resultant of all direct and indirect changes taking place in the energy system of complex buildings due to rationalisation.

Chapter 8 is devoted to life cycle assessment (LCA) applied in the ecological analysis of complex buildings. It has been stressed that in complex energy systems input-output analysis ought to be used in the life cycle inventory stage. The ecological component of LCA has been presented. This chapter contains an example of an LCA of a typical office building.

Chapter 9 deals with algorithms concerning preliminary design, the aim of which is to choose the optimal structure of the energy management of complex buildings. A systems approach to the procedure of the formation of variants of energy management in complex buildings is presented, as well as Lagrange’s decomposition method for choosing the optimal variant. An example of the application of the descriptive model of energy management is given concerning complex buildings, and also an example of an optimisation model for choosing the energy management of an industrial-urban complex.

The sequence of the chapters in this book is didactically justified. The first three chapters introduce the reader to systems analysis. The next two chapters acquaint the reader with the energy management of complex buildings. Then it becomes possible to present the mathematical energy-ecological system models of the energy management of complex buildings, and the presented examples permit reader to become more familiar with the systems approach to the energy management of complex buildings. LCA is an extension of previously presented energy and ecological system models, comprising the full life of complex buildings. The last chapter is largely based on the systems methods presented in the previous chapters.

This book is partially the result of the strategic program PBS-3/RIE 6/2010 “Integrated system of the reduction of energy consumption in the course of exploiting the buildings”. The authors wish to express their gratitude to the Polish National Centre of Research and Development. The authors of this book wish to express their gratitude to Professor Jan Szargut, the Nestor of Polish thermodynamicists, for his influence on their scientific formation in thermal engineering and his agreement to quote some of his diagrams in this book. They also wish to thank Mr Feliks Lipski (M.A.) for consulting with respect to the English text and Miss Katarzyna Widziewicz (M.Sc.), Mr Michal Budnik (M.Sc.) and Mr Paweł Gładysz (M.Sc.) for preparing a part of the computer composition. Thanks are also due to Dr. Maria Kolokotroni from Brunel University in England for her cooperation in analysing the night cooling ventilation system and the LCA. Last but not least we wish to express our gratitude to Madam Fran Macdonald for her proofreading of the text.

Chapter 1

INTRODUCTION INTO SYSTEMS ANALYSIS

Process analysis and systems analysis are two approaches to energy-ecological analysis. Process analysis is a mechanistic approach that dominated the last centuries, although the notion of system has been known since the time of Aristotle. Systems analysis was formally discovered again just before the Second World War by the biologist Ludwig von Bertalanffy, although the methods of systems analysis were already known (e.g., Leontief's "input-output analysis"). System is defined as a set of elements mutually connected and also with the environment, in which the system is situated. A characteristic feature of organised systems is their hierarchical structure. Every system is also characterised by a given degree of coherence and independence. Generally, systems are divided into natural and artificial ones. The features differentiating both these systems are conformability and optimisation. The general theory of systems comprises, first of all, the mathematical theory of the system, and secondly system engineering. This book deals with the latter. There are two fundamental methods of describing systems, viz., causal description (input-output analysis) and intentional description (optimisation models). The system structure is usually presented either by technological diagrams or structural matrices.

1.1. The idea of the system and its environment

Both the conception of system and system approach are as old as European civilization. It is generally accepted that Aristotle's formulation "the whole is more than the sum of its parts" constitutes a first attempt to define the system problem[3]. In researches, past centuries, however, the mechanistic approach prevailed in which every problem is divided into parts and investigated separately. Thanks to its application so many inventions were made that for many, many years no changes to this approach seemed necessary. In biological sciences, however, it has been observed that in the application of this method the interconnections between particular parts of an organism are neglected. And, as mentioned, only shortly before the Second World War the system approach was discovered anew by the biologist Ludwig von Bertalanffy [1], who stated not only that investigations of the parts must be supplemented by investigations of the whole but that there exists a separate discipline which he called theory of systems dealing with investigations of the whole. For the first time the general theory of systems was presented in the years 1937÷1938 by L. Bertalanffy in his lectures at the University of Chicago [1].

The word "system" comes from Greek and means composition or connection. According to Bertalanffy [1, 3] a system may be defined, as stated above, as a set of elements connected with each other and also with the environment. More particularly, we may say that a system is an intentionally determined set of elements and relations between these elements and their properties [5]. Such properties are features of the respective objects, the relations being interconnections existing between the respective parts and the whole. Due to these relations the whole displays properties which do not occur in its parts. The notions "arrangement" and "system" are frequently treated as synonyms. In contradistinctions to arrangements, however, systems may not only be real objects but also abstract ones (e.g., science, education). A real system is arranged in compliance with the physical elements composing the whole, whereas an abstract system is arranged according to its functions, with the properties characterising the whole. Further considerations in this book concern real systems.

Every system is situated in some environment. Any separation of a concrete system is equivalent to defining the rest as belonging to the environment. Whether a given element belongs to the system or to the environment depends on the subject of investigations, the concrete object and the aim of investigations. The environment of the system comprises all the objects not belonging to the system, the properties of which affect the system, simultaneously undergoing changes due to the influence of the system. We may distinguish physical, economic and social environments. The physical environment comprises among others, also other existing systems, the state of technology and accepted technical standards, as well as the natural environment (geographical situation, raw material resources, climate, flora and fauna), as well as actual and future experimental and design endeavours. The system cooperates with the environment in the sense that its elements can influence the elements of the environment and vice versa. The interdependence between the respective elements of the system is usually much stronger than between system and environment.

Each system can be divided into subsystems. A subsystem in which there do not exist any further subsystems of a lower order, is called an element. Each system, again, may be a subsystem belonging to a higher level system (supersystem).

The fundamental system operation comprises the analysis and the synthesis. The former one consists in investigations concerning the behaviour of the system basing on its structure. The search for the system structure based on the knowledge of its behaviour is called synthesis.

1.2. Properties of systems

The term “system” means “order”. The measure of arrangement in a system is the degree of deviation from the state of thermodynamic equilibrium, defined by Shannon as redundancy [2]:

$$R(\tau) = \frac{S_{\max} - S(\tau)}{S_{\max}}, \quad (1.1)$$

where:

$R(\tau)$ - redundancy at the moment τ ,

$S(\tau)$ - entropy of the system at the moment τ ,

$S_{\max}$ - entropy of the system at the equilibrium state.

In the case of an ideally arranged (perfectly organised) system $R = 1$. A completely disorganised (chaotic) system corresponds to $R = 0$. A factor favouring the arrangement of the system is a control. Systems arranged according to the defined functions of the it respective elements are called organised systems [2].

A characteristic feature of organised systems is their hierarchical structure. This property consists in the fact that the respective elements of the system are systems of a lower order (subsystems), and the given system being considered constitutes a subsystem of a higher order (supersystem). This property permits the system to be divided into subsystems. In each system with a hierarchical structure we can distinguish elements of the highest (central) level, which in the given system have no superior elements, as well as elements of the lowest level (zero level) without any subordinate elements. Between the central system and zero systems there may occur intermediate levels whose elements are simultaneously subordinated to elements of the higher level and superior to the elements of a lower level. The complexity of hierarchical structures is a special feature of large energy systems.

The property called centralisation is connected with systems that have a hierarchical structure. This process consists in incrementing the coefficients of interdependence in one of the subsystems. Thus slight changes in the subsystem involve considerable changes in the whole system. The subsystem which plays a deciding role in the operation of the entire system is called the controlling part of the system. Centralisation is a property varying in time and resulting in an increase (progressive centralization) or reduction (progressive decentralization) of the controlling function.

Every system is characterised by a given degree of coherence which consists in a connection of the respective elements so that a change in any one of them involves changes in the other elements and vice versa; a change in any arbitrary element depends on all the other elements of the system.

Independence is the opposite of coherence. In such a case no connection exists between the elements of the system, so that a change in any one of the elements does not lead to changes in any other elements of the system. In this case changes in the system are the sum of individual changes in the elements. Interactions are then equal to zero. In the case of an absolute independence of the elements, there is no system. It is rather a set of functionally mutually independent elements.

Coherence and independence are extreme cases of the same property of the system. Both these quantities may occur in various degrees. The degree of coherence and independence changes in time. The transition of a coherent system to an independent one is called progressive division. Progressive integration is characterised by the intensification of already existing connections between the elements of the system and increasing number of connections or the inclusion of new elements and connections into the system, as a result of which the coherence increases. In contradistinction to progressive division, progressive integration involves an increase in the organisation of the system.

Other properties of the systems worth mentioning are adaptability, stability, and equifinality. Adaptability is the property of the system permitting to react to changes in the state of the system and in the state of the environment favouring its further existence. The stability of the system is the ability to decrease automatically the effect of disturbances up to their complete elimination. Equifinality is a property which permits the system to achieve some given aim starting from various preliminary states.

The intelligence of the system is a property that permits the system to understand why some given state has come into being and the consequences of changes in the coupling and the utilisation of these perceptions in order to educate the system. This education is a process of changing the structure, the organisation or properties of the adaptive system caused by iterative stimuli, in order to achieve a more effective behaviour of the system.

1.3. Classification of systems and their characteristics

In 1.1 above, we drew attention to the division of systems into real and abstract ones. Real systems may be subdivided into small and large systems according to the number of their elements. The number of internal connections between the elements of the system decides about its complexity, viz., [6]:

- a) simple system with the least possible number of connections $l = n - 1$, where n denotes the number of elements,
- b) complex system with a number of connections within the range $n - 1 < l < n(n - 1)$,
- c) particularly complex system with a number of connections $l > n(n - 1)$.

From the viewpoint of connections with the environment we can distinguish:

- a) open systems exchanging substance, energy and information,

- b) closed systems characterised by a lack of exchange of the substance; in this case energy is exchanged by means of such forms of transportation which do not require the substance (heat, mechanical or electrical work); also information is exchanged with the environment,
- c) separate systems exchanging neither substance, nor energy nor information.

As far as the variability of the states of the systems in time is concerned we can distinguish static and dynamic systems. Dynamic systems display structural or functional structures changing in time. Dynamic systems may also be divided into deterministic and probabilistic ones. We have to do with a deterministic system when the knowledge of the values of the respective variables in any given moment permits the state of the system to be determined explicitly in any later moment. In the case of a probabilistic system its new state can be predicted only with some probability.

From the viewpoint of human activities in constructing the systems, they may be divided into natural and artificial ones. Natural systems are encountered in nature. Their existence depends particularly on their ability to adaptation, consisting in the fact that the system adapts itself to changes in the environment in a way most favourable for its further operation.

Natural (biological) systems are characterised by the so-called homeostasis. This is the ability of the system to keep certain quantities within ranges conditioned by the possibility of its adaptation in spite of even considerable changes in external conditions [5]. The phenomenon of homeostasis occurs thanks to mechanisms of self-regulation, connected with the application of the feedback. In natural systems the number of feedbacks is considerable. Thus they are ultrastable systems. The system is ultrastable if after exceeding one feedback loop a next loop with another range of operation is included.

Artificial systems, dealt with further on, are systems constructed by humans. Some features are common to both groups of systems, but there are differences of essential meaning. Coherence and independence are common features of natural and artificial systems. Centralisation and adaptability are more characteristic of natural systems. In artificial systems feedback mechanisms are either not active or too weak. Therefore, artificial systems are unstable. Artificial systems display other properties such as conformability and optimisation, which do not occur in natural systems [2,5]. Conformability consists in a system with a structure that matches the environment. Optimisation, on the other hand, consists in ensuring the best possible adaptation of the system to the environment. This issue does not concern natural systems, because during their long period of development they can adapt themselves to the environment in the best possible way.

An essential difference between natural and artificial systems is their reliability, which determines the probability with which the system will display in some given process the required and previously determined behaviour. Reliability comprises freedom from failure, durability, and the possibility of repair. Freedom from failure is the ability of the system or element to keep up its efficiency in given conditions of functioning and in a defined interval of time. Durability is the ability of the system or element to be used under given conditions and at an adequate level of service. The possibility of being repaired consists in preventing, detecting and removing damages which may occur incidentally (breakdown), or may be due to aging of the system or element.

In contradistinction to artificial systems, natural systems are characterised by a high reliability due to the fact that the respective subsystems are composed of a large number of reserve elements. Artificial systems are constructed economically without an excess of elements. Their structure is usually, therefore, a series structure. For this reason the failure of any element involves the breakdown of the whole system.

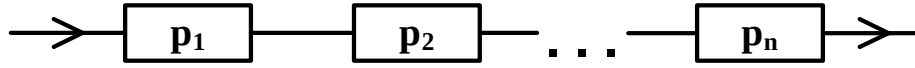


Fig. 1.1. Series structure of system

The reliability of a system composed of elements connected in series (Fig. 1.1) results from the assumption of mutual independence of the respective elements:

$$p = \prod_{i=1}^n p_i, \quad (1.2)$$

where:

p - probability of lack of failure in a system (reliability of the system),

p_i - probability of lack of failure in the i -th element (reliability of the i -th element),

n - number of elements in the system.

As can be seen in formula 1.2, the reliability of the system decreases with the growing number of serially connected elements. Such a conclusion is justified when we assume that in any element " i " $p_i = 0$ is not valid and that all the elements $p_i = 1$ do not occur simultaneously. An increased in reliability of any element involves an increase in the reliability of the whole system.

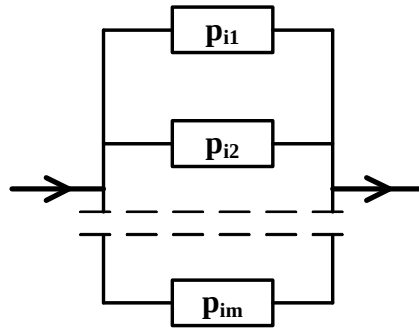


Fig. 1.2. Parallel structure of the system

The reliability of an artificial system can be effectively improved by introducing an adequate number of parallelly by connected reserve elements (Fig. 1.2). In the case of $(m_i - 1)$ reserve elements the reliability of the i -th element results from the equation [5]:

$$p_i = 1 - \prod_{j=1}^{m_i} (1 - p_{ij}), \quad (1.3)$$

where:

p_{ij} - reliability of the j -th element, which is a reserve of i -th element,

m_i - number of all elements with the same function (base element and reserve elements) in the i -th element of the system.

The reliability of the whole system composed of n elements connected in a series, each of them having $(m_i - 1)$ reserve elements, may be expressed by the equation [5]:

$$p = \prod_{i=1}^n \left[1 - \prod_{j=1}^{m_i} (1 - p_{ij}) \right]. \quad (1.4)$$

An increase in the reliability of each element and in the number of parallelly connected elements improves the reliability of the system.

1.4. An excerpt of the general theory of systems

The general theory of systems is a logical-mathematical domain, the aim of which is to formulate and derive principles applied in various kinds of systems. The general theory of systems, originally connected with biology, is the result of attempts to apply thermodynamics in biology. Bertalanffy stressed the fact that Onsager's thermodynamic of irreversible processes is an example of the systems approach [1]. An essential feature of the theory of systems is its generality and abstractness, as well as the fact that it investigates the features of systems and not their physical phenomena by means of mathematical methods.

The fundamental method of the general theory of systems consists in assigning the isomorphism of laws concerning various domains of science. In the general theory of systems isomorphism is deduced from the analogy of physical phenomena (e.g., heat conduction and electric current). These analogies may also concern absolutely different phenomena, e.g., the flow of liquids and interbranch flow according to Leontief's "input-output analysis" [4]. Isomorphism occurring between two systems is to be understood as a mutually explicit correspondence between the elements of one system and some other system, and the existence of the same relations between the corresponding elements of both systems. Two concrete systems may be determined as mutually isomorphic if both of them can be presented by the same mathematical model. Isomorphism between two mathematical models permits conclusions to be drawn about the isomorphism between two concrete systems represented by the given mathematical systems. The similarity of algebraic equations or differential equations is a kind of mathematical isomorphism. An example of two isomorphic concrete systems is firstly the phenomenon of steady-state heat conduction in solid bodies without internal sources of heat and with a constant thermal conductivity, and secondly the phenomenon of a steady-state field of the electric potential in a conductor with a constant electric conductivity. The respective differential equations, being mathematical models of the considered systems, take the form:

$$\nabla^2 T = 0, \quad (1.5)$$

$$\nabla^2 U = 0, \quad (1.6)$$

where:

T - temperature,

U - electric potential,

∇^2 - Laplace operator.

In this example the mathematical models are isomorphic. Thus, concrete systems presented by these models are also isomorphic. There is an analogy between temperature and the electric potential, thermal conductivity and electric conductivity, between thermal resistance and electric resistance, thermal capacity and capacitance, and the heat flux and current intensity. Electrical analogue models were formerly used to solve differential equations of heat conduction in the case of bodies with a complex geometry.

The general theory of systems distinguished the following domains of investigations:

- mathematical theory of systems,
- system engineering,
- philosophy of systems.

The *mathematical theory of systems* comprises the general theory of systems in its narrower meaning, cybernetics, control theory, theory of information, set theory, graph theory, game theory, and simulation theory. Based on set theory, the system S may be defined as follows [3]:

$$S \subset \times \{V_i : i \in I\}, \quad (1.7)$$

where:

V_i – element of the system,

I – set of indices.

The relation defined by the Eq. 1.7 denotes that the system S is a subset of the Cartesian product on the elements V_i of the system.

If I is the finite set, we get [3]:

$$S \subset V_1 \times V_2 \times \dots \times V_n. \quad (1.8)$$

The Cartesian product $V_1 \times V_2 \times \dots \times V_n$ is a set of all the vectors $[v_1, v_2, \dots, v_n]$, so that $v_i \in V_i$ for $i = 1, 2, \dots, n$.

Each element v_i represents the feature or characteristics of the system expressed in categories in which the given system is described. The set V_i comprises all possible ways of observing the given feature. Thus, the system is a set of all the combinations of the state in which the elements of the system occur.

The definition of the system expressed by the relations (1.7)-(1.8) is characterised by a high degree of generality. In the case of real systems this formulation is to be understood, for example, as a set of algebraic or differential equations.

There are two fundamental methods of describing the system:

- input-output method, also called causal description,
- a method that makes use of the objective function, also called intentional description.

In the case of the former method the group of input elements and the group of output elements are separated [3]:

$$X = \times \{V_i : i \in I_x\}, \quad (1.9)$$

$$Y = \times \{V_i : i \in I_y\}, \quad (1.10)$$

The system is then the relation determined between the input and output sets.

$$S \subset X \times Y. \quad (1.11)$$

In intentional description, besides the input and output sets, the set of decision variables M and set of values of the objective function V are to be distinguished. Moreover, the objective function G and the set of restrictions P are given [3]:

$$P : X \times M \rightarrow Y, \quad (1.12)$$

$$G : M \times Y \rightarrow V, \quad (1.13)$$

where the set V is determined in such a way that each subset contains a minimum element, which means that some particular case of intentional activity is considered as aiming at the minimisation of some function.

The system S , determined by the Eq. (1.11), is defined as follows. The pair $(x, y) \in S$ for $x \in X$ and $y \in Y$ merely when such a value $m_x \in M$ exists, so that for each $m \in M$ we have [3]:

$$G(m_x, P(x, m_x)) \leq G(m, P(x, m)), \quad (1.14)$$

$$y = P(x, m_x). \quad (1.15)$$

This means that for each input $x \in X$, the output $y \in Y$ is matched in such a way that the objective function attains its extremum value in the previously assumed particular case simultaneously satisfying the restrictions.

System engineering comprises software and hardware. Software results from the application of the general theory of the system to technical, economic and social problems. Hardware deals with technical equipment and comprises control, automation and computerisation.

The immediate aim in the software is the optimisation of output values in compliance with the given criteria. Thus, system engineering is strictly connected with operations research [2]. Whereas, however, operations research usually deal with operating systems, the purpose of system engineering is to plan and design new systems. Principally this concerns preliminary designing. In system engineering and operations research the stages of the procedure are the same, comprising:

- formulation of the problem,
- elaboration of the mathematical model,
- solutions of the problem based on the model,
- verification of the model and of the solution,
- checking the solution,
- practical realization.

System engineering makes use of several modern scientific domains, such as identification, modelling, simulation, computer science, optimisation, theory of reliability and so on. The technique of simulation is particularly useful, permitting:

- the influence of a larger number of variables than in the case of physical experimenting to be checked,
- the costs to be lowered and the time of investigations to be shortened thanks to the simulation model,
- conditions actually not yet existing to be provided and checked.

Philosophy of systems comprises problems connected with changes in the orientation of scientific thinking caused by the introduction of the notation of system as a new scientific paradigm. This part of the general theory of system is not dealt with in this monograph.

1.5. The structure of systems

According to the definition, a system is composed of elements interacting with each other by means of inputs and outputs. Every element is assumed to have at least one input and one output, each of them attaining at least two values. The system structure may be presented graphically by block diagrams or oriented graphs, and by structural matrices.

The states of inputs and outputs of the elements are presented by the vectors $\mathbf{X}$ and $\mathbf{Y}$, respectively. The coupling of the elements is based on the fact that the output values of one element can be input values in another element. If the k -th element is characterised by the output vector $\mathbf{Y}_k$ and the l -th element includes the input vector $\mathbf{X}_l$, then between the output vector $\mathbf{Y}_k$ of the k -th element and the input vector $\mathbf{X}_l$ of the l -th element we have the equality [5]:

$$\mathbf{Y}_k = \mathbf{C}_{kl} \cdot \mathbf{X}_l. \quad (1.16)$$

The connections between the considered elements are expressed by the binary coupling matrix $\mathbf{C}_{kl} = [c_{ij}]$ defined as follows:

$$c_{ij} = \begin{cases} 1, & \text{if the } i\text{-th output of the element } k \text{ is simultaneously } j\text{-th input of the element } l, \\ 0, & \text{the opposite case.} \end{cases}$$

In order to get a connection between the element k and element l , the matrix $\mathbf{C}_{kl}$ or $\mathbf{C}_{lk}$ must contain at least one non-zero element. The coupling matrix displays the property that in each row and column occurs at the most one element equal to one [5]. In the case of n elements there are n^2 equations of the type (1.16) taking into account internal connections between the elements.

The binary matrix $\mathbf{C}$ composed of submatrices of the coupling $\mathbf{C}_{kl}$ is called the system structure matrix:

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_{11} & \mathbf{C}_{12} & \dots & \mathbf{C}_{1n} \\ \mathbf{C}_{21} & \mathbf{C}_{22} & \dots & \mathbf{C}_{2n} \\ \dots & \dots & \dots & \dots \\ \mathbf{C}_{n1} & \mathbf{C}_{n2} & \dots & \mathbf{C}_{nn} \end{bmatrix} \quad (1.17)$$

The distribution of non-zero submatrices leads to the following conclusion concerning the characteristics of the system structure [5]:

- if the row k and the column k contain at least one non-zero matrix each, the k -th element is an internal element of the system,
- if the row k contains only zero submatrices, the k -th element is a boundary output element, i.e. its outputs lead to the environment,
- if the column l contains only zero submatrices, the l -th element is a boundary input element i.e. its inputs are taken over from the environment,
- if the row k and the column k contain only zero submatrices, the k -th element does not belong to the system,
- the occurrence of more than one non-zero submatrix indicates a splitting of the internal outputs, which means a dispersion of the influence,
- the occurrence of more than one non-zero submatrix in the column indicates focusing of the internal inputs, i.e. a concentration of their influence,

- the occurrence of non-zero matrices of coupling above the main diagonal denotes the occurrence of serial couplings,
- the occurrence of non-zero submatrices along the main diagonal denotes the occurrence of self-couplings (internal connections in the element),
- the occurrence of non-zero submatrices below the main diagonal denotes the occurrence of feedbacks.

The boundary input element is an element with which the other elements belonging to the system are not connected (i.e., the components of the input vector are not components of the output vector of any other element of the system). The boundary output element is an element which is not connected with the other elements of the system (i.e., the components of the output vector of the boundary element are not components of the input vector of any element belonging to the system). The set of boundary elements constitutes the surface of the system to which corresponds to the set of all zero columns and rows of the matrix $\mathbf{C}$.

An element which is not a boundary element is an internal element of the system. The set of all columns and rows of the matrix $\mathbf{C}$ including at least one non-zero submatrix is the interior of the system. A close system has no boundary elements. An open system is a system which contain boundary elements.

The matrix $\mathbf{C}$ of the system structure can be supplemented with the row vector $\mathbf{C}'_o$ and the column vector $\mathbf{C}''_o$ comprising the connections of the system with the environment [5]. The vectors $\mathbf{C}'_o = [c_{oi}]$ and $\mathbf{C}''_o = [c_{ko}]$ are defined as follows:

$$c_{oi} = \begin{cases} 1, & \text{if the input of the } i\text{-th element is from the environment,} \\ 0, & \text{the opposite case.} \end{cases}$$

$$c_{ko} = \begin{cases} 1, & \text{if the output of the } k\text{-th element leads to the environment,} \\ 0, & \text{the opposite case.} \end{cases}$$

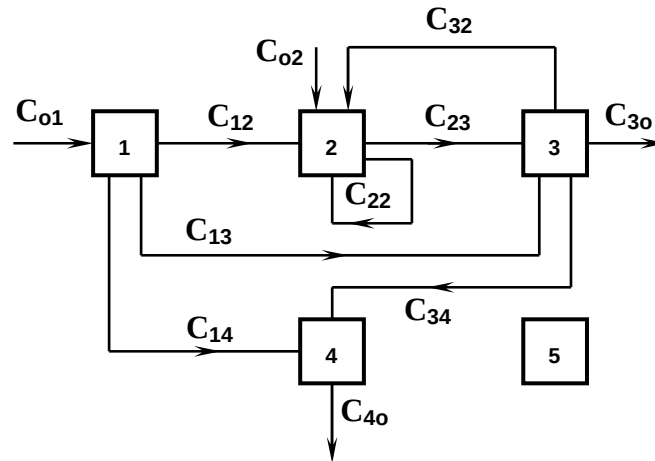


Fig. 1.3 Example of connections between the elements in the system

The non-zero submatrices of the vectors $\mathbf{C}'_o$ and $\mathbf{C}''_o$ prove the existence of connections between the system and the environment. Figure 1.3 presents example adapted from Mynarski [5]. System consists of five elements, whose connections between the outputs and inputs are

expressed by the coupling matrix. The matrix C of the system structure and the vectors C'_o and C''_o comprising the connections of the system with the environment look like this:

$$C = \begin{bmatrix} 0 & C_{12} & C_{13} & C_{14} & 0 \\ 0 & C_{22} & C_{23} & 0 & 0 \\ 0 & C_{32} & 0 & C_{34} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C'_o = [C_{o1} \quad C_{o2} \quad 0 \quad 0 \quad 0]$$

$$C''_o = \begin{bmatrix} 0 \\ 0 \\ C_{3o} \\ C_{4o} \\ 0 \end{bmatrix}$$

Based on the matrix C the following structural features of the system can be distinguished:

- element 1 is the boundary input element and element 4 is the boundary output element,
- element 5 does not belong to the system,
- in the element 2 occurs self-coupling,
- between the elements 3 and 2 there is a feedback.

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Chapter 2

LARGE ENERGY SYSTEMS

Complex buildings belong to large energy systems, which are continuously developing artificial systems with a hierarchical structure. The chief system in the hierarchy is the domestic energy system divided into five subsystems, four of which (solid fuels, liquid fuels, gaseous and electroenergy systems) comprise the whole country and the fifth one - the thermal energy system - is a set of municipal, industrial-municipal and industrial systems of feeding heat carriers (hot water and steam). The subsystem of transporting and transmission of primary and final energy carriers is the next stage in the hierarchical structure. Lower stages are centres of the supply of final energy carriers. A still lower stage comprises the consumers of final energy, among them complex buildings.

A characteristic feature of large energy systems is the inseparable inclusion of the consumers of fuels and energy in the structure of the systems. Large energy systems are, besides their internal connections, characterised by a complex system of external connections with other branches of the domestic economy and the environment. Particular attention ought to be paid to interconnections of large energy systems with the natural environment mostly causing negative ecological results.

A characteristic feature of large energy systems is their continuous development. Hence, there exist dynamically direct connections and back-connections. Information plays an important role, both in controlling large energy systems and in designing and programming their development. From the viewpoint of credibility, input information is divided into deterministic, probabilistic, probabilistic incomplete, and incomplete ones. The level of credibility of available input information determines the type of the mathematical model used to analyse the development of large energy systems.

Large energy systems are characterised by an uncertainty of solutions of their optimal development. This indefinability results from the impossibility of determining explicitly the future really optimal stage of the system, due to the incompleteness of input information. Large energy systems are also characterised by the economic stability of the solutions. Both these features involve the formulation of the domain of uncertainty of optimal solutions. The active share of humans in making decisions is for this reason indispensable.

The algorithm for controlling large energy systems cannot be described in a strictly mathematical way. The final solution for planning or designing can be obtained in the course of iterative balance calculations.

2.1. Characteristics of large energy systems

Large energy systems are continuously developing artificial systems with a hierarchical structure in which people are organically connected with the controlling or controlled part of the system. It is therefore a system of the type “man-machines-environment”. Large energy systems belong to that group of artificial open systems which determine the most important relations in the national economy.

Depending on the point of view of investigations, large energy systems may be considered to be technical systems of the cybernetic type or economic systems. Technical systems are characterised by the following features:

- connections between the elements are of a material (energy) character,
- the processes are continuous in time,
- the mathematical description of physical laws describing the fundamental phenomena and changes in the system is rather accurately known,
- humans plays the role of the operator (controller) of the system,
- the controlled part of the system is machines.

Systems of the economic type are characterised by:

- the active role of humans in the controlling and controlled parts of the system and their interconnections,
- the lack of a precise mathematical description of the behaviour of the system,
- a special role of social-economic impulses in the case of optimal control.

Depending on the aim of the analysis and the timing of its performance such a large system may be either a technical or an economic system [3,4]. Thus, for instance, the domestic electro energy system considered from the operative-disposition point of view is a large technical system of the cybernetic type with a hierarchical structure. From the viewpoint of national economy, however, it is an economic system; the main aim of the control is the correct organisation of the activities of groups of people who are responsible for the supply of electricity without break-downs.

Large energy systems are characterized by the following specific features:

- the constitution of the entire energy system as a materially compact system due to interconnections of the power grid, pipelines, and internal connections resulting from the partial mutual substitution of final products,
- the existence of numerous external connections resulting from the universality and considerable importance of the final product (e.g., electricity) in the national economy,
- active influence on the development and localisation of other branches of industry in spite of realising the required services of the energy system for the national economy as a whole,
- inseparable inclusion of the consumers of fuels and energy in the structure of the systems,
- special role for automatic control of the operation of the systems and operative supply of fuels,

- impossibility of applying the classic transport model in energy systems, which assumes that consumer are assigned to the deliverer; such a model of control can play only an auxiliary role,
- particularly large dimensions and, as a result, a high degree of complexity.

2.2. Hierarchical structure of large energy systems

The hierarchical structure of large energy systems is based on both productive and territorial connections. Productive connections are vertical connections and territorial ones horizontal connections. Territorial connections are important because the mutual substitution of the production manufactured by large energy systems occurs directly on the territorial level.

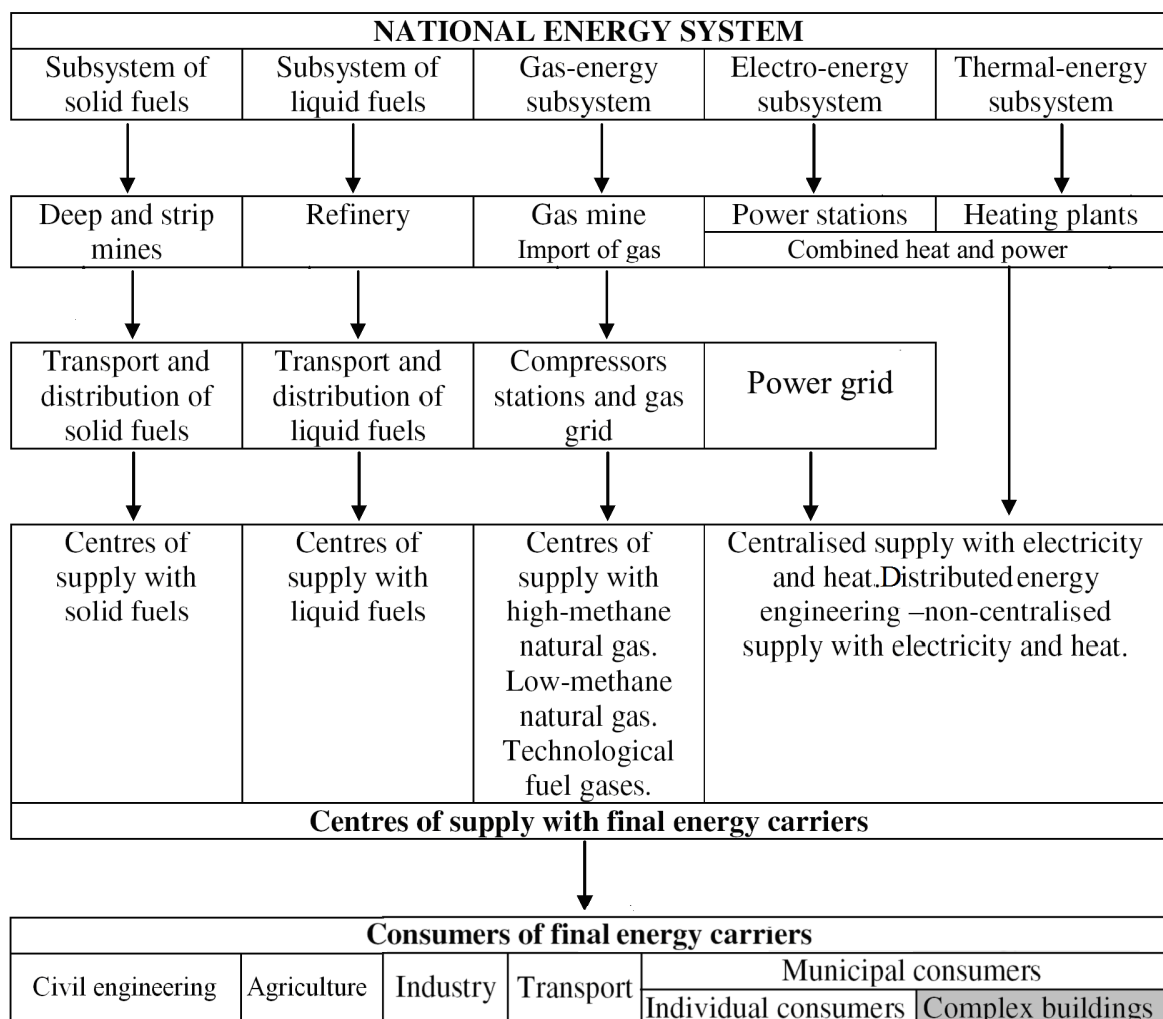


Fig. 2.1 Scheme of the hierarchical structure of large energy systems adapted from Mielentiev [3]

Figure 2.1 presents a diagram of the hierarchical structure of large energy systems [3]. At the top of the hierarchy there are five subsystems constituting the national energy system. On a lower level there are productive subsystems of primary and final energy, as well as installations realising the import, in many countries mainly of liquid fuels and high-methane natural gas. On this level, electro-energy and thermal-energy subsystems have common productive installations, viz., CHP plants realising the production of heat and electricity in

cogeneration. The next level consists of transporting subsystems for solid, liquid and gaseous fuels, as well as electricity, which ranges all over the country.

The level of energy consumers, which in the presented hierarchical structure is conventionally the last level, is joined to the level of the centres supplying final energy carriers. These centres are considered to be sites of concentration of production, distribution and consumption of final energy carriers. Such centre may be an industrial plant, a town, an agricultural region, and also large complex buildings (e.g., airports, supermarkets, and recreation centres). On the level of energy-supplying centres we have the thermal-energy subsystem (e.g., district heating system), which due to the economic range of transporting steam and hot water is not considered to be on the level of the whole country. On this level we have distributed energy systems, realising non-centralised delivery of heat and electricity, as well as local resources of natural gas with a large content of nitrogen, technological fuel gases, and waste liquid fuels (e.g., soft asphalt). The level of consumers comprises industrial plants, municipal and individual consumers including complex buildings, and transport.

2.3. External connections

These are the connections of the given system with other hierarchically higher systems or systems on the same level. In investigating large energy systems, only those external connections, which influence its operation perceptibly are to be taken into account. Figure 2.2 presents a diagram of fundamental external connections with the domestic energy system [2]. To these belong the following groups:

- connections resulting from interbranch flows between the domestic energy economy and other branches of the domestic economy,
- restrictions concerning financial and material means, as well as the availability of human resources and sites; they should result from the optimisation of the trends in the development of the domestic economy,
- connections resulting from the interdependence of the national energy economy and non-energy branches in the process of technical progress,
- social-economic connections between the energy economy with in the domestic economy and the environment,
- connections resulting from international commerce.

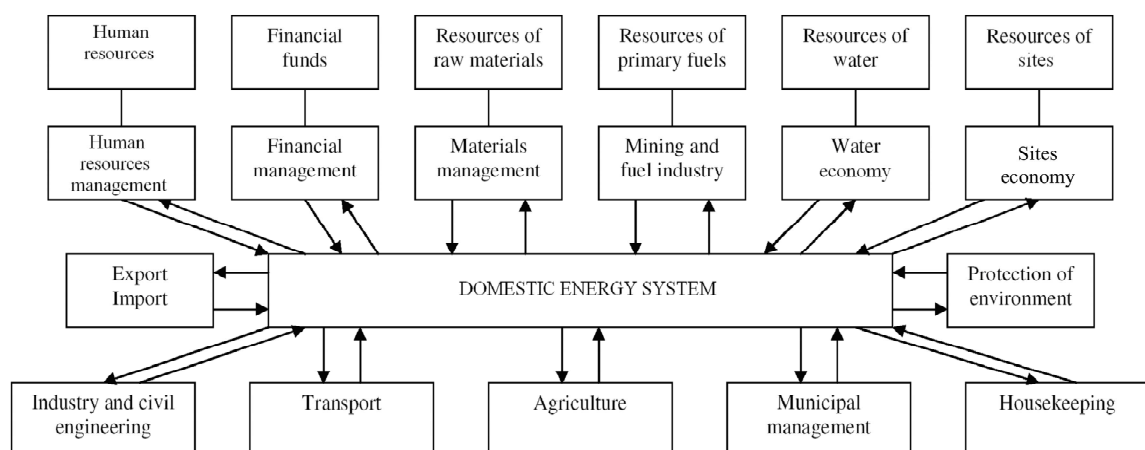


Fig. 2.2 Scheme of external relations of the domestic energy system adapted from Mejro [2]

External connections are characterized by their inertia. This means that additional demands of the energy systems for machines, installations and equipment cannot be satisfied at once, and neither can the demands of the domestic economy for additional amounts of energy carriers. This inertia must be taken into account in investigations concerning energy systems together with the existing system of interbranch connections in the domestic economy.

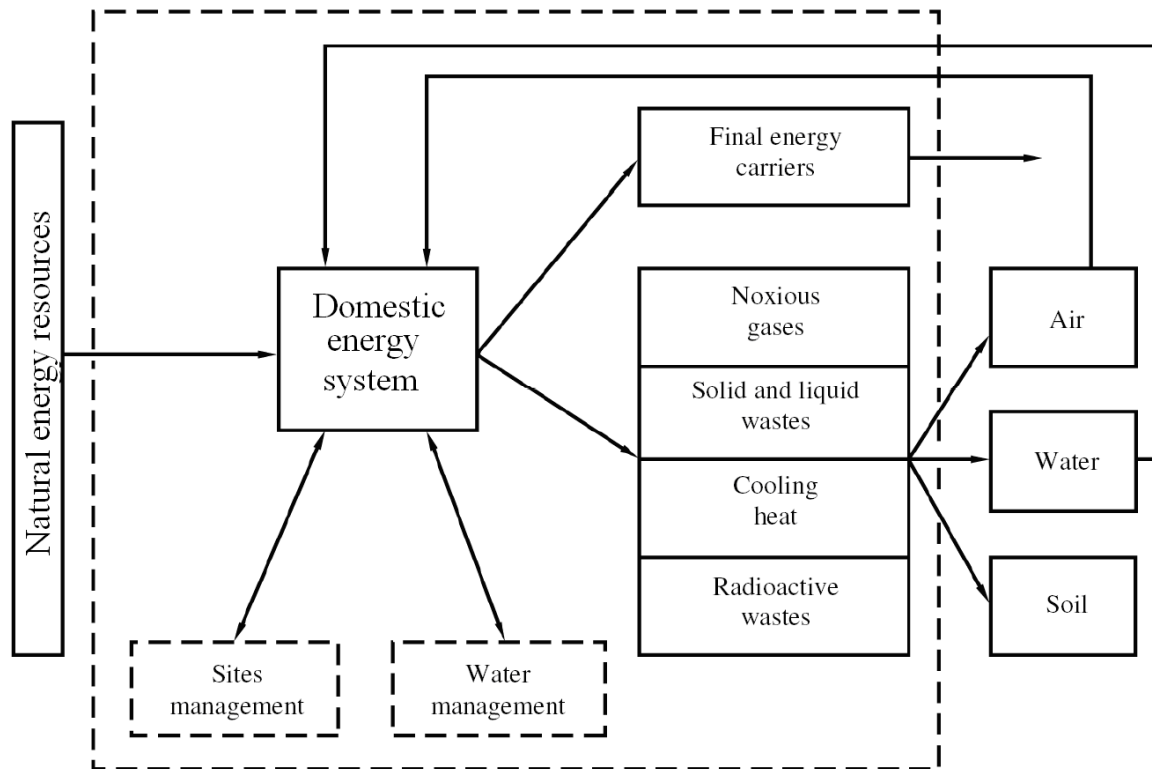


Fig. 2.3 Scheme of energy and ecological relations adapted from Mielentiev [4]

Particular attention ought to be paid to interconnections of the domestic energy system with the natural environment mostly bringing about negative ecological results. Figure 2.3 presents a diagram of energy-ecological interconnections [4]. The domestic energy system derives primary energy carriers, water and air from nature. An undesirable effect of the energy systems is the carrying away of harmful gaseous emissions, solid and liquid waste, heat from cooling systems, and radioactive waste into the environment.

Power stations, CHP plants and heating plants fired with fuels, particularly coal, emit considerable amounts of sulphur and nitrogen oxides and flue dusts into the environment. These are mainly local effects. The emission of CO_2 and other greenhouse gases influences the global changes in the climate. Installations that desulphurise flue gases may radically reduce the emissions of sulphur oxides. This, however, involves a 15 to 20 per cent increase in capital expenditures and a decrease in the efficiency of producing electricity (the power rating of desulphurising installations amounts to 3 to 4 per cent of the power rating of the energy unit). Another problem is the emission of NO_x the noxious effects of which exceeds that of SO_x by six to ten times. The emission of dust can be reduced by a higher efficiency of dust collection plants, the development of district heating systems, by supplying individual consumers with fuel of a better quality, and improvement in the state of exploitation and control of combustion processes. The application of fluidised beds in the boilers is connected with a decrease of sulphur and nitrogen oxides.

The cooling heat in power stations is carried away to the environment by applying open or closed water cycles. The passing of heat with the cooling water to lakes or rivers in open cycles may negatively affect the biological realm. Large irreclaimable losses of cooling water in cooling towers with closed cycles increase the deficiency of water in any given region. Cooling towers also involve a deterioration of the local climate near the power station, particularly in winter [6].

The development of the energy system is connected with the economy of sites and often also negatively influences the state of the soil. Thus, for instance, the construction of a strip mine of lignite leads to the formation of a depression crater and consequently to a lowering of the underground water level, which negatively affects the agricultural production. In power station with four GW, which covers a site of 200÷300 ha, not counting the dumping ground for ashes and the water reservoir, in the course of ten years of exploitation, the ash dumping ground increases each area up to 8 km² [2].

Of fundamental importance for the environment is the problem of the localisation of radioactive cemeteries. A nuclear power station with a power rate of 1 300 MW produces every year about 200 m³ of solidified wastes, of which 80 per cent being low-active, 15 per cent are medium-active and five per cent high-active [1]. Up to now the storing of low- and medium-active wastes, this problem may be considered to be solved. In the case of high-active wastes, intensive investigations are actually underway. Similarly as in the case of solidified medium-active nuclear wastes, also the best localization of solidified high-active wastes is a stable geological formation (deposits of rock-salt and clay, as well as rock mass).

According to the assessment of experts capital expenditures for the reduction of harmful effects on the environment resulting from the development of energy systems may usually amount to five to ten per cent of the entire expenditure for the development of the energy systems.

2.4. Characteristic of dynamic connections and back-connections in large energy systems

A characteristic feature of large energy systems is their continuous development, i.e., quantitative growth connected with simultaneous structural changes. Hence, there exist dynamical connections, divided into direct and back-connections. The former are characterised by the influence of previous stages upon later ones. The latter are characterised by the effects of later conditions in the development of the systems on earlier stages. Such strong connections necessarily lead to the optimisation of the system from the end of the time horizon to the initial state.

The intensity of the occurrence of dynamic connections in the system is the higher as the time horizon is longer. The longer the time horizon, the more the results of the choice of elements must be taken into account, but on the other hand the error of input information increases with time. Practically, it is assumed that the maximum time for planning amounts to 15 years, while the maximum time for predicting is 25 to 30 years.

If the dynamic connections are very strong and the horizon of optimisation is stable, the problem arises as to how to divide this time into shorter periods mostly comprising five years. In order to optimise a gas-energy and electro-energy system it is indispensable to investigate the conditions of operation of these systems in various seasons of the year (at least in summer and winter).

During the development of a large energy system turning points may occur (e.g., the commissioning of nuclear power plants) which require particularly accurate researches. These turning points introduce discontinuity in the usually continuous process of the development of large energy systems.

The dynamic features of large energy systems have been manifested for many years, not only in the programming of their development, but also in their actual functioning. Thus, for instance, the chief aim of controlling an electro-energy system is the optimal distribution of the production over 24 hours between the particular power stations, taking into account starting losses and the chosen filling and emptying conditions of water reservoirs in hydro-electric power stations, as well as other factors with essential dynamic features. These are not static and determined problems but rather dynamic, usually probabilistic ones. The connections in other domestic energy subsystem (gas- and thermal-energy ones) have a similar dynamic character.

Mathematical models concerning an energy system with dynamic connections ought to apply dynamic programming, although this, radically increases the dimensions of the problem. Therefore, while solving dynamic problems it is recommended that either a specific method of constructing nonlinear dynamic models or wider constructed and generalised linear models are applied. In this case linear block programming is applied [3].

2.5. Information about investigations of large energy systems

Information plays an important role in planning and programming the development and designing large energy systems and their control. Information has the following function [3]:

- it is a form of presentation of the internal and external connections of energy systems,
- it permits the selection of the most adequate variants in the development of the systems,
- it affects changes of the parameters of the structure and functioning of the systems.

In energy systems, which are open systems, information is divided into external and internal information. The former comprises mainly information about:

- geophysical conditions and geological discoveries,
- trends and rate of development of the national economy,
- technical progress in energy engineering and those branches of industry which are connected with energy,
- changes in the economic proportions in industrial branches influencing essentially the economic proportions in large energy systems,
- structure and level of the prices of fuels and raw materials,
- restrictions in capital expenditures, material and human resources.

Internal information comprises, among other data, information about:

- the structure of the energy systems,
- conditions and structure of the supply of energy carriers,
- energy characteristics of machines and installations,
- degree of reliability of energy installations,
- mutual replaceability of energy carriers,
- degree of waste energy recovery.

The significance of information depends on its substantiality, sufficiency, actuality and credibility. Of essential importance is information (or some part of it) which decisively influences the achievement of the aim of the analysis. Scarcity of information, as well as its excessiveness hamper analysis and decrease its effects. Delayed information may prove to be without any value.

As far as the degree of credibility is concerned, input information is divided into [5]:

- deterministic information,
- probabilistic information,
- probabilistically incomplete (insufficiently determined) information,

- incomplete information (insufficiently determined).

If exact values of the considered quantities are known, information has a deterministic character. To this kind of information belong some discrete quantities, for instance the types of construction of machines and installations, the shape of the thermal diagram and the number of energy devices. This group also comprises so-called conventional deterministic information [3]. In practical calculations due to only small changes in some parameters of the system depending on its conditions of operation, changeability in time, and measurement errors, information concerning them may be assumed to be deterministic [5].

The probabilistic form of presenting input information concerns random variables with accurately known statistical distributions (distribution function or density of probability). Data of a probabilistic character include, among other data, geophysical information (e.g., duration curve of the ambient temperature). Probabilistic characteristics are most often obtained based on statistical information concerning the past, assuming probabilistic stability. If the available statistical data cannot be considered as representative due to differences between past and future conditions, we have a probabilistic instability. In this case probabilistic characteristics of the past cannot be extrapolated for the future. Then investigations concerning trends are inevitable.

In the case of incomplete probabilistic information the statistical distributions are not accurately known. Information about a given quantity is presented by a series of statistical distributions or by the range of values which the analysed quantity may take.

Incomplete information does not display features of statistical stability and is based on variants of possible values without determining the degree of probability with which the given quantity may be expressed by the respective values.

In the two latter groups we may include information about technological indices and predicted costs of energy installations, the regime of their exploitation, and the strength of new kinds of applied materials.

In investigations concerning large energy systems only a small part of input information is deterministic or probabilistic form. Most input data are incomplete (insufficiently determined) information involving an uncertainty of input data.

Among the indices belonging to input information we can discern a group of indices whose mean values are explicitly defined in which the uncertainty is the result of incidental deviations from the average value. These indices may be considered as random values of the expected value. For some indices in this group, the function of statistical distribution can be defined accurately, considering the information to be a probabilistic. In most cases, however, based on assessments of experts, several possible distribution functions are accepted. This leads to an incomplete probabilistic quantitative description of input information.

In the case of processes and installations to be introduced in future the input data (technical-economical characteristics and characteristics of new materials) are preset as variants. The quantitative assessment of the variability of this group of indices is an assessment of the inaccuracy of each variant of data and of the probability of realising the given variant. Otherwise the assessment must be expressed by experts.

Taking into account incomplete input information, the problem of optimisation is much more extensive. Therefore, a selection of input information, and rejection of unessential information that does not affect the results, are very important. Experience indicates that about two thirds of information which theoretically might influence the solution, has practically no meaning [3].

The occurrence of incomplete or probabilistic incomplete information in the set of input data leads to uncertainty in the results of the problem to be solved. This uncertainty is also due to simplifications resulting from mathematical modeling, and the aggregation of input data, as well as errors in measurements and numerical calculations.

One of the fundamental means of preventing the harmful influence of incomplete information on the development of the system is secure optimal reserves of possible capacities, raw materials and final products, and to prepare for other variants in the development of energy systems.

2.6. Indefinability of optimal solutions and their economic stability

Large energy systems are characterised by an uncertainty of solutions of their optimal development due to the overlapping of incidental phenomena and processes with their development. This indefinability results from the impossibility of explicitly determining the future really optimal state of the system, due to the incompleteness of input information concerning the development of large energy systems in the future. Input information always includes some element of uncertainty and even for this reason alone the solution cannot be explicit. Large energy systems are also characterised by an economic stability of the solutions. This means that a certain number of structurally different variants in the development of the system corresponds practically to the same capital expenditure. Near the extrema the objective function is comparatively flat.

The inaccuracy (incompleteness) of input data together with the economic stability of solutions involves formulations of “areas of uncertainty of optimal solutions”, each of which may be treated as an optimal one in various actual possible conditions (combination of input data). This feature of a large energy system results from its definition as a developing set of elements, a typical feature of which is the incomplete cognisability of its quantitative characteristics; hence the impossibility of realising an optimal control by means only of a formalised method. The active role of humans in making decisions is indispensable [4].

The reason for the economic stability of solutions in the development of large energy systems is that only 12 to 15 per cent of the capital expenditures are connected with the optimised set of installations. The remaining expenditures are assigned to already existing installation or new undertakings whose profitability is certain [3].

The feature of economic stability of large energy systems permits some simplifications to be introduced into optimising calculations without any risk of “losing” the most economic solution. On the other hand, however, this feature complicates the calculations because, near the optimum, solutions frequently differ greatly in their technical parameters.

2.7. Control in large energy systems

The control of large energy systems requires the formation of automatic control systems on the respective levels of the hierarchy of the domestic energy system. The aim of automatic control systems is to collect, process and analyse information which is indispensable for those who have to choose the best solutions for the domestic economy and realise them. The complexity of automatic control systems consists in the following interconnected elements:

- controlled plant (system or hierarchical complex of actual systems),
- control elements,
- information subsystem warranting the archivisation and monitoring of data,
- a set of mathematical models,
- computer centre for data processing and optimising calculations.

The advantages of applying automatic control systems are the attainment of more accurate solutions in planning and design, a better use of the data base, and higher organisational efficiency in the management of energy systems. In order to achieve effective

operation of automatic control systems on the respective levels in the hierarchy of the energy systems, informational, methodological, technical, organisational and mathematical uniformity is indispensable.

The algorithm for controlling large energy systems cannot be described in a strictly mathematical way. The mathematical model is merely an approximated image of the real system. An attempt should, therefore, be made in the control process to attain a cooperation of the formal (mathematical) method of attaining an optimal solution and the experience (intuition) of experts. Mathematical models, particularly in economic systems, are merely “advisers of man” when making decisions. In the case of automatic control systems on the respective levels in the hierarchy of the domestic energy system rational proportions must be kept between formal calculations and human heuristic activity. The control algorithm ought to be adapted in order to be applied to control actual incomplete input data. Taking into account the uncertainty of input data leads to the indefinability of optimal solutions concerning the future state of the energy system. The choice of the final solution depends to a large extent on human decision.

The algorithm for controlling large energy systems is an iterative algorithm. The initially accepted solutions for a higher level of the hierarchy of the automatic control system are transmitted for the purpose of exact calculations to the lower level, and after the return transmission to the higher level the obtained results are used to state precisely the preliminary solutions.

In the control of large energy systems four main time horizons are to be distinguished:

- long-term strategy (mostly 15 years),
- medium-term strategy (5 years),
- short-term strategy (detailed annual plan),
- current control throughout the year.

The tasks of the system of balance calculations concerning the domestic energy system are:

- to determine the fundamental optimal proportion of the development of the national energy management, balancing the development of other branches of the national economy,
- to determine annual and current plans for supplying the country with fuels, electricity and heat,
- to control the current realisation and prospective plans for developing the domestic energy management and their correction.

In the case of large energy systems planning is an iterative process. The final solution is obtained in the course of iterative balance calculations concerning the domestic energy system and its respective branches together with systems of balance calculations concerning other domains (e.g., transport and metallurgy). The first stage of planning is the calculation of rational levels of the consumption of various energy carriers all over the country. The aim of the second stage is to calculate the optimal and mutually balanced production and distribution of energy carriers. The third stage deals with external connections and consists in matching the plan of the development of the domestic energy system and its branches with the environment (domestic economy).

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CHAPTER 3

MATHEMATICAL MODELLING AND OPTIMISATION OF ENERGY SYSTEMS

The mathematical model of an energy system denotes a set of interdependences (equations, inequalities, logical conditions, etc.) which provide an approximated image of the properties, the functioning and development of an actual system. The most effective trend in mathematical modelling of energy systems is the application of the property resulting from its hierarchical structure. This is connected with the decomposition of the global optimisation task, based on the division of the global problem of optimisation into several subproblems, solved independently and then coordinated.

One of the most effective methods of decomposition is Lagrange's method. It can be proved that the vector of Lagrange's multipliers corresponds to the vector of the unit costs of energy carriers. This means that the matrix method of determining the unit costs of energy carriers is a coordinating procedure in the task of decomposition of the global optimisation of energy systems.

The fundamental tool of mathematical modelling of energy systems, applied in this book, is however, Leontief's "input-output" analysis. This method can be applied in various economic systems, from any single economic enterprise (e.g., an energy system in a complex building) up to the country as a whole. Based on input-output models dynamic linear models of optimisation may also be constructed.

Modelling the development of large energy systems is strictly connected with forecasting. The forecasts are based on procedures containing mathematical, logical and heuristic components. One of the earliest and most frequently used is the trend-extrapolation method. Recently the following methods have been recommended: the econometric and "end-use" analysis, which latter was preceded by the so-called "branch balances" method. The most often applied optimisation method is the economic approach with ecological elements. The most important, however, is the criterion of social effectiveness, so-called "quality of life". Besides economic and ecological components, such an approach to the optimisation of energy systems includes also a political component, a social component, state of health, state of education and so on. In the optimisation of energy systems restrictions in the development of energy systems must also be taken into consideration. The main ones are the need to protect the natural environment, the availability of raw materials and fossil fuels, limited water resources and investment expenditures. Due to the uncertainty of input data and the economic

stability of solving any energy system, adequate methods of choosing a solution in conditions of indefinable optimal solutions must be found.

3.1. The essence of mathematical modelling

Modelling is defined as a method of recognising the characteristics of actual systems by means of a conformable model of the system. The aim of the model is to obtain information about an actual system which is difficult or even impossible to obtain by means of direct investigations of the system. Physical modelling based on the theory of analogy is applicable to the analysis of deterministic processes. Mathematical modelling permits investigations of only those parameters of the actual system whose mathematical description is known and which are interconnected by mathematical equations concerning both the actual system and the model. In contradistinction to physical modelling, mathematical modelling is connected with a change in the kind of system, viz., an actual system is investigated by means of a mathematical system constructed in agreement with the modelled actual system [15].

Under the term "mathematical model of the system" we understand there to be a set of interdependences (equations, inequalities, logical conditions, etc.) which provide an approximate image of the properties, the functioning and development of an actual system [15], because it is not possible to obtain a model which is an ideal reflection of reality. Every model renders the analysed system in a simplified form. It is practically impossible to take into account all the details, but on the other hand simplifications should not go too far.

In the process of mathematical modelling the following stages can be distinguished:

- separation of the system and selection of those properties and connections of the system which are the aim of the planned investigations,
- construction of the mathematical model (mathematical system) in which the selected properties and connections of the actual system can be tested in a simpler way than in the actual system; by constructing the mathematical model the investigated system is set free of connections which hamper its testing, but testing them is not the aim of investigations,
- investigations concerning the properties and connections of the system and also the laws of its development by means of the mathematical model; the mathematical model becomes the object of experimentation, providing possibilities of investigating numerous phenomena with various values of the input data, even when they are not realisable at the present moment in the actual system,
- application of the obtained results of investigations concerning the model in the actual system; this is possible due to the conformity of the elements and connections in the model with the elements and connections in the actual system,
- verification of the model with the aim of checking the effects of simplifications on the solution obtained by means of the model; in the case of mathematical models of physical systems such a verification is performed experimentally; large energy systems can be verified by means of calculations based on a model of previous periods.

The most effective trend in mathematical modelling of energy systems is the application of the hierarchical property. This permits the decomposition of a large optimisation problem. The division is performed basing on weak connections in the system. It should not affect strong connections.

3.2. Types of mathematical models and their application in investigations of energy systems

The mathematical models may be divided into descriptive and decisive (optimising) ones. Among the descriptive models we can distinguish interpreting models and "input-output models". The former describe causal-effective dependences between the elements of the system. The latter are based on information concerning the input and output states of the system.

As to applied methods of calculations, mathematical models can be divided as follows:

- linear and nonlinear,
- static and dynamic,
- deterministic and probabilistic,
- statistical and strategic,
- continuous and discrete.

In investigations of large energy systems descriptive models of the input-output types are applied, first of all optimizing models. An optimising model principally also comprises a descriptive model. For instance, balance equations of energy carriers, being a descriptive model, are simultaneously a part of the set of restrictions of the optimising model. The optimising model may be used to describe the whole set of admissible solutions and permits an optimal solution to be found [15, 17].

The optimising model consists of two parts: the objective function resulting from the assumed criterion and the set of restricting equalities and inequalities. In the optimising model two kinds of quantities are to be distinguished, viz., decisive variables and parameters. The former are quantities determined on the basis of optimisation. The parameters comprise imposed quantities (e.g., factors of the objective function or the right-hand side restrictions). The character of information concerning the parameters of the model is due to the (already mentioned) division of mathematical models into deterministic, probabilistic, statistical and strategic ones.

When all the parameters affecting the result of optimisation are constant and known, the model is a deterministic one. The result of optimisation is explicit. To each decision corresponds one and only one value of the objective function. In the case of a simple technical system mathematical models can be solved by means of differential calculations (e.g., optimisation model applied to distribute the load between the power units of the power station). In modelling large energy systems, mathematical programming is applied. If all the relations in the model are linear (objective function and restrictions), we have a linear mathematical model which can be solved by linear programming. Practically, many non-linear problems may be reduced to a linear form by transforming or simplifying them (e.g., by expansion of a non-linear function to Taylor's series, neglecting terms of higher orders). If neither the linear model nor traditional method of differential calculus can be used, non-linear programming is applied. There is no general method which would permit any given non-linear model to be solved. There are, however, several methods which may be adapted to the non-linear problem to be solved.

A model is probabilistic if at least one of the parameters is a random variable with a known statistical distribution, and the remaining parameters are deterministic ones. Methods used to solve this type of model are mainly based on the probabilistic calculus.

Statistical and strategic models are characterised by an uncertainty of information about the parameters. In the statistical model the incomplete knowledge of the parameter consists in the fact that it is not a random variable or it is a random variable with an unknown statistical distribution. A representative statistical test may provide additional information about the

parameter. Methods used to solve this class of models are provided by mathematical statistics. For strategic models only a limited set of values is known in which the parameter can be assumed. Game theory is applied to solve strategic models.

For the purpose of solving some of the afore mentioned optimisation models, dynamic programming is applied. This concerns cases in which a series of successive decisions occurs, and the optimal one is to be determined.

In large energy systems mathematical modelling is used to solve the following problems:

- long-term planning and design; on the level of a plant it also includes complex preliminary design optimisation of new types of installations,
- medium-term planning and design; on the level of the plant it also includes automation of designing a separate installation,
- annual planning and economic control,
- operative control of stores and reserves on the level of the domestic energy system; control of the technological regimes on the level of the respective subsystems of the domestic energy system and control of technological processes, in plants producing and processing energy carriers.

The main requirements expected from mathematical models of energy systems are:

- sufficient accuracy in rendering the properties of the actual system,
- accuracy in the results of calculations corresponding to the accuracy of input information,
- simplicity of and facility in using the model,
- acceptable rate of solving them in practice.

These requirements are rather difficult to be achieved due to:

- an immense complexity of connections in large energy systems, non-linearity, continuity of development, and incomplete cognisability of their quantitative characteristics,
- the fact that controlling and the controlled part of large energy systems involve groups of people whose activities cannot be exactly expressed by mathematical models,
- impossibility of checking objectively the accuracy of the decision while it is being taken.

Based on experience gathered so far, the principles of constructing and applying mathematical models concerning large energy systems, which consists in the subsequent correction of the solutions, may be assumed [11]. The domestic energy system can be optimised with sufficient accuracy by means of dynamical linear models. As a preliminary step, the subsystems of solid, liquid and gaseous fuels are optimized, as well as, electro-energy, thermal-energy and nuclear energy subsystems. Next, these subsystems are subjected to exact optimisation specifying them precisely:

- choice of thermodynamic parameters of the installations,
- conditions of their application,
- parameters and conditions of applications in normal and break-down situations of the mains (electrical and pipelines) of the system,
- problems of reliability and redundancy.

At the stage of precise optimisation of the subsystems in domestic energy systems dynamical non-linear models are used. Non-linear models are also applied for the purpose of optimisation in the course of designing energy utilities, as well as in computer control systems.

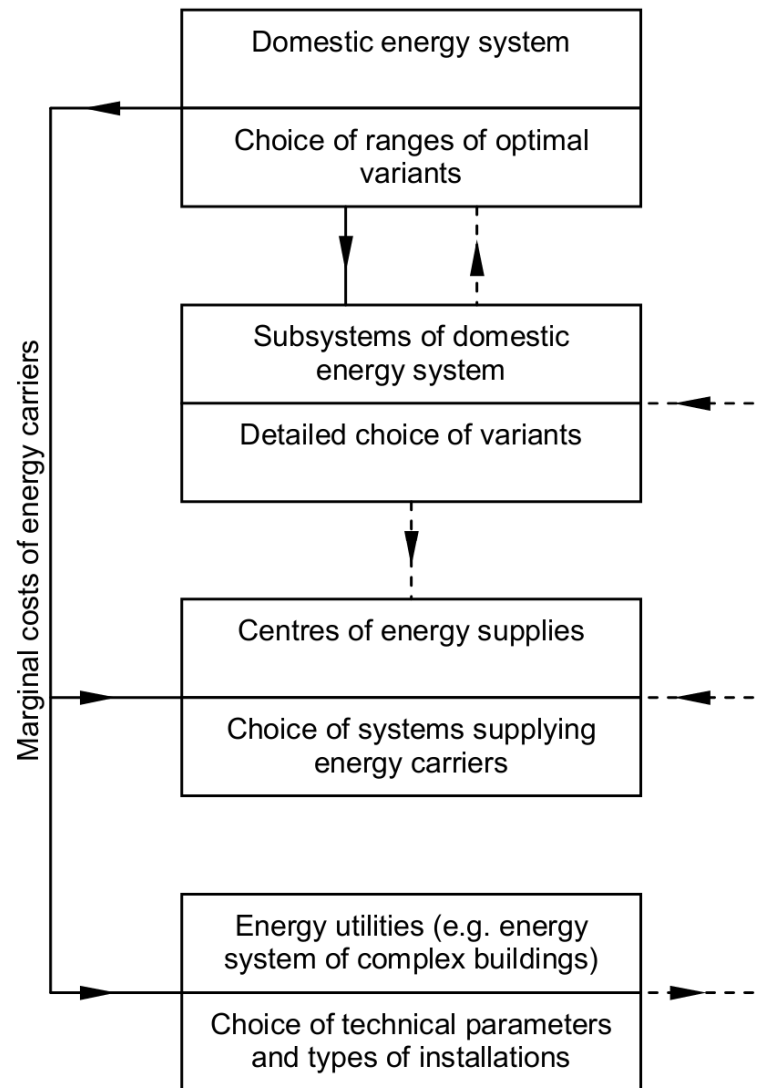


Fig. 3.1. Diagram of the optimisation of large energy systems (—direct connections,---feed-back connections) adapted from Mielentiev [12]

Figure 3.1. illustrates the sequence for optimising large energy systems making use of mathematical models [12]. On the level of the domestic energy system, the range of economically equivalent variants in the development of subsystems is determined by means of linear models. This is the result of the indefinability of optimal solutions due to the uncertainty of input data. Next, by means of non-linear models of the respective subsystems, the best one is selected (sometimes based on complementary criteria).

In optimising the domestic energy system, the so-called marginal costs of energy carriers are determined (balancing the costs of energy carriers) [4, 12, 14]. A sufficient stability of these indices permits them to be applied in the independent optimisation of systems on a lower hierarchical level. The application of the marginal costs permits the effect of the optimised element of the energy system to be taken into account with all the other branches of the energy management.

3.3. Application of the input-output analysis

According to Wassily Leontief, the author of „Input-output economics” [8], and Nobel-prize winner in 1973, “Input-output analysis is a method of systematically quantifying the mutual interrelationships among the various sectors of a complex economic system. In practical terms, the economic system to which it is applied may be as large as a nation or even the entire world economy, or as small as the economy of a metropolitan area or even a single enterprise” (as well as complex buildings - annotation of the authors). Continuing from Leontief’s book– “In all instances the approach is essentially the same. The advantage of the input-output analysis is that it permits the disentanglement and accurate measurement of the indirect effects” (pp.17 and 18) [8].

The structure of linear models is usually based on Leontief's “input-output analysis”. In case of a static model, the structure of Leontief's input-output table is based on the following assumptions:

- the production process is divided into “n” branches, each of them manufacturing only one product,
- the global production of each branch is assigned practically to be used in other branches, the other part being processed in the same branch, and the rest being the final product,
- the consumption of the product of the “i-th” branch is directly proportional to the global production of the “j-th” branch,
- quantities quoted in the table are independent of time; they may be expressed in natural or monetary units.

Table 3.1. presents the principal idea of Leontief’s input-output analysis.

Table 3.1.

Table of interbranch flows according to Leontief’s input-output analysis.

Production branch	Main product	External supply	Interbranch flows				Final product
			1	2	...	n	
1	G_1	D_1	G_{11}	G_{12}	...	G_{1n}	K_1
2	G_2	D_2	G_{21}	G_{22}	...	G_{2n}	K_2
...	...	...	...	...	...	...	...
n	G_n	D_n	G_{n1}	G_{n2}	...	G_{nn}	K_n

Assuming a linearity between production and consumption, the balance equation for the “i-th” production branch takes the following form:

$$G_i + D_i = \sum_{j=1}^n a_{ij} G_j + K_i \quad (3.1)$$

in which

$$G_{ij} = a_{ij} G_j \quad (3.2)$$

where

G_i, G_j - global production of the i-th or j-th branch,

D_i - supply of the i-th product from outside,

G_{ij} - consumption of the i-th product in j-th branch,

a_{ij} - technical coefficient of the consumption of the i-th product per unit production of the j-th branch,

K_i - final production of the i-th branch.

In modelling the domestic economy, external supplies are imported, whereas the final product is exported or increases the stores. In the case of large energy systems, the coefficients a_{ij} correspond to the indices of the direct unit consumption of energy.

Expressed in matrix notation the set of balance equations takes the form:

$$\mathbf{G} + \mathbf{D} = \mathbf{A}\mathbf{G} + \mathbf{K} \quad (3.3)$$

where:

$\mathbf{G}$ - n-vector of global production,

$\mathbf{D}$ - n-vector of supplies from outside,

$\mathbf{A}$ - matrix $n \times n$ of the technical coefficients of consumption,

$\mathbf{K}$ - n-vector of final products.

If in equation (3.3) the vector $\mathbf{G}$ is the only unknown quantity after its transformation, we get:

$$\mathbf{G} = (\mathbf{I} - \mathbf{A})^{-1} (\mathbf{K} - \mathbf{D}), \quad (3.4)$$

assuming that the matrix $(\mathbf{I} - \mathbf{A})$ is a nonsingular matrix, i.e., the determinant $|\mathbf{I} - \mathbf{A}| \neq 0$. If the vectors $\mathbf{G}$ and $\mathbf{D}$ are not known, the problem can be solved by means of linear programming.

The inverse matrix $(\mathbf{I} - \mathbf{A})^{-1}$ of $(\mathbf{I} - \mathbf{A})$ contains elements which in econometrics are called coefficients of total expenditure because they take into account both the direct and indirect consumption resulting from a network of interconnections between the respective branches of production. In the case of large energy systems the elements of the matrix $(\mathbf{I} - \mathbf{A})^{-1}$ are indices of cumulative energy consumption, corresponding to the coefficients of total expenditure.

W. Leontief devotes three chapters in his monograph [8] to problems concerning the emission of pollutants handled by input-output analysis. Among others, he says, "Pollution is a by-product of regular economic activities". In our opinion the term "by-product" ought to be applied only to useful products. For instance, in a cogeneration process realized in a CHP plant, electricity is a by-product because its production depends strictly on the demand for useful heat. If, however, the term "by-product" is used to mean pollutants, the term "harmful" should be added, assigning the term "by-product" merely to useful product. SO₂ contained in flue gases in power stations, for example, is a harmful waste if not utilised well, but gypsum as a product of wet desulphurisation installation is a useful by-product.

In Chapter 6 we distinguish between main production and by-production in modelling the energy management of complex buildings. We also discuss the model of cumulative emissions based on the principle of input-output analysis.

Leontief's input-output model is applied in various economic systems, from single economic enterprises (or their energy management, e.g., energy systems of a complex buildings) up to the country as a whole or a group of countries forming an economic unit. In the case of modelling the energy management of industrial plants or complex buildings the input-output equations must be supplemented by elements that characterising the actual system being modelled (e.g., differentiating the basic and peak production, and by-production of energy carriers) [16].

W. Leontief also writes in his book "The next step in input-output analysis is the development of dynamic models of the economy to bring the approximations of the method that much closer to the actual processes of economics. The dynamic input-output analysis requires more advanced mathematical methods; instead of ordinary linear equations it leads to systems of linear differential equations" (p.18) [8].

3.4. Dynamic linear models of optimisation

Dynamic models are characterised by the fact that the effects of the decision become visible not only in the present but also later. Therefore there are interconnections not only between activities carried on in the course of one period, but also between activities performed in that and any other period. Dynamic linear models of optimisation can be solved by means of the following methods:

- as static tasks of linear programming,
- by decomposition,
- applying special methods of linear dynamic optimisation.

Practically the most frequently applied method is the first one in which the dynamic linear problem is transformed into problems of linear programming and solved by means of the simplex method. Dynamic models of linear programming consist of several static submodels constructed for the respective periods, into which the calculated length of time has been divided [11,12].

“Moving forward”, applying static solutions to linear tasks concerning the respective stages, the effect of direct dynamic interconnections is realised. They are expressed by balances of the production capacities of the respective branches at the beginning and at the end of each stage of the calculated length of time.

Reverse dynamic connections are effected by a secondary optimisation of static solutions “moving backward” over the respective stages of the calculated length of time. In this way the results brought about in the system by the introduction of every new element are explained and the solutions achieved by “moving forwards” are expressed more precisely. Thus, the calculation procedure is an iterative one, reaching its end as soon as the assumed accuracy has been attained. In the case of the occurrence of weak reverse connections, the procedure of optimisation can be solved only “moving forwards”, by solving statically the linear tasks for each stage of the calculated length of time. Then is a so-called conventional-dynamic or conditional-dynamic model, most often applied in optimising the development of large energy systems.

The decomposition method consists in the division of the global task of optimisation into partial ones, the solution of which must be coordinated in order to ensure an agreement between global and local criteria. Special methods of dynamic linear optimisation include methods applying the function of punishment for transgressing the restrictions [11,12].

3.5. Decomposition of the optimisation problem

One particularly effective methods of mathematical modelling is the method based on the division of the global problem of optimisation into several subproblems solved independently and then coordinated. This method is called decomposition [13]. Thus, decomposition is a process of the division of the global optimising problem into subproblems and the elaboration of a procedure of coordination. Decomposition comprises two stages for its realisation:

- the solution of separate subproblems of optimisation,
- the solution of the coordination task.

Of essential importance for the decomposition is the degree of coherence of the system which determines the dimension of the coordination task, because there are systems with such a high degree of coherence that decomposition does not reduce the amount of processed information compared with a non-decomposed task. In decomposition, use is made of the hierarchical feature of energy systems.

The problem of decomposition is connected with the following tasks:

- formulation of separate subproblems of optimisation,

- creation of subproblems in a form which is numerically effective and easily coordinated,
- construction of the coordinating procedure.

The main difficulty in dividing the global task of optimisation of the system into partial subproblems is formulation of the optimising criterion for each subsystem. This difficulty is due to interconnections between the subsystems. In optimising a separate subsystem, we must be convinced that it will be effective from the viewpoint of the global criterion of the system. This results from the fact that in the optimisation of the selected subsystem the intervention of no other subsystem is taken into account.

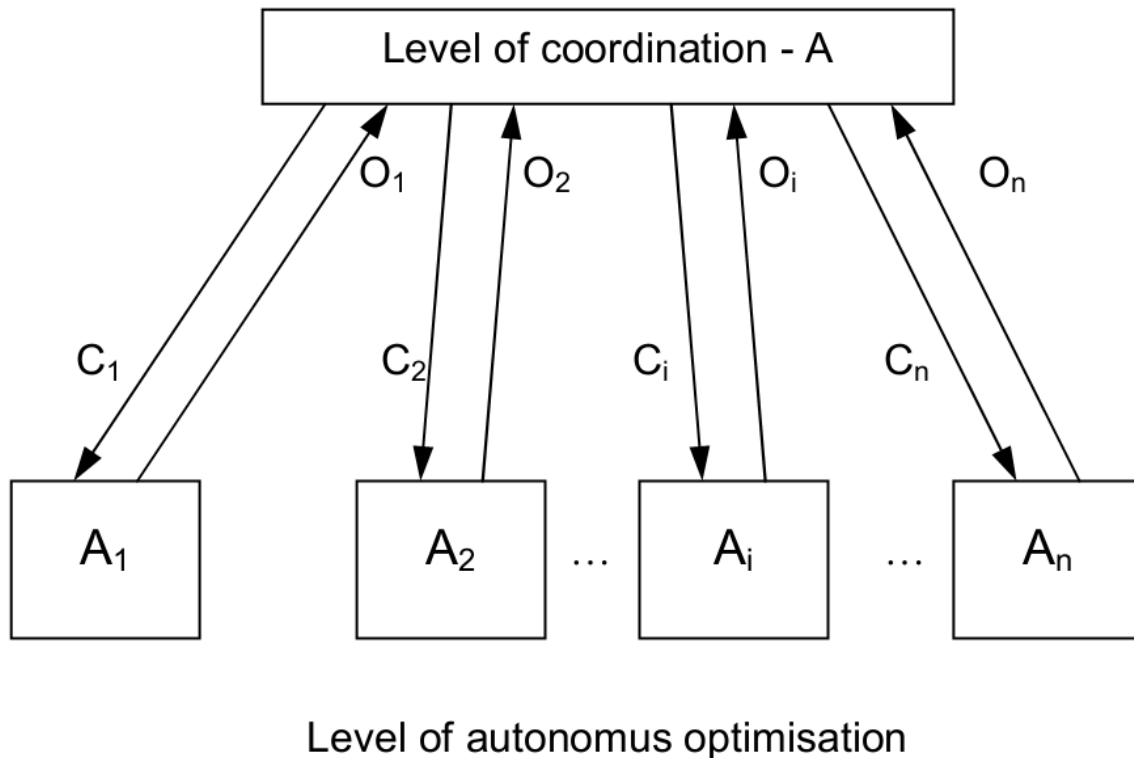


Fig. 3.2. Diagram of the structure of decomposition algorithm adapted from Popyrin [13]

Figure 3.2 illustrates schematically a general diagram of the structure of the decomposition algorithm [13]. The upper and lower hierarchical levels have been distinguished. On the upper level of the hierarchy the central algorithm A comprising first of all the coordination procedure, is obligatory. On the lower level, the local optimisation algorithms $A_1, A_2, \dots, A_n$ have been formulated. In order to ensure a conformity of the autonomous optimisation criteria on the lower level with the global criterion, the set of the information $c_1, c_2, \dots, c_n$ resulting from the coordination procedure is transmitted from the level A to the level A_i , of autonomous optimisation. After autonomous optimisation of every subsystem, the set of information $o_1, o_2, \dots, o_n$ is transmitted from the lower level to the upper level of coordination. Then on the upper level of the hierarchy the subsequent iteration begins, resulting in an improved set of new information $c'_1, c'_2, \dots, c'_n$ which is to be sent to the lower level of optimisation. Thus, the procedure of the decomposed optimisation task is iterative [13].

It is important to stress that it is not possible to formulate optimising criteria for each separate subsystem taking into account the interconnections between the subsystems based on the global optimisation criteria of the system, and thus to reduce the optimisation of the

system to the task of a single optimisation of each separate subsystem. The existing methods of decomposition permit to reduce the optimisation problem to an iterative procedure, where an autonomous optimisation of the respective subsystems occurs in every iterative step. The iterative procedure of decomposition is necessary to connect the individual optimisation tasks. Every solution on the upper level of the hierarchy requires a correction of solutions on the lower level and vice versa. The number of iterations depends on the degree of complexity of the given mathematical model, the accuracy of input information, and the precision of the optimisation method. One of the most effective methods of decomposition is Lagrange's method of undetermined multipliers ("Lagrange multipliers") [13].

3.6. Characteristics of the development of large energy systems

A characteristic feature of large energy systems is their continuous development, i.e., their quantitative growth and simultaneous structural changes. The aim of the optimisation is to ensure the best possible development trend for the system in the given horizontal time. In large energy systems both regular and selectively explicit development trends occur, as well as accidental phenomena and processes overlapping them which cause a deviation of the development from objective trends. Therefore, large energy systems are characterised by an uncertainty of solutions concerning their optimal development, i.e., it is impossible to determine the future state of the system unequivocally.

The development of energy systems depends on the predicted available means of production. The time passing from the prediction to the realisation of the enterprise may be as long as a score of years or even longer. A longer time (exceeding 20 years) is required for structuring a new coal basin, hydro-power station or plant producing energy machinery. The longest time (up to 30 years) is required to investigate and implement new types of energy machines and installations.

Investigations, concerning the development trends of large energy systems, are strictly connected with mathematical modelling of such systems. Three stages are to be distinguished in the construction of the model. The first stage is a mathematical model or heuristic procedure for the elaboration of the scenario, which is strictly connected with prognostication in energy systems. In the course of the second stage the direct demand for energy carriers is determined by simulated mathematical models. The third stage comprises the construction of the optimisation model with the purpose of choosing the optimal structure of the system of gaining, processing and consuming energy carriers. This latter stage involves the formulation of the criterion of optimisation and the choice of an adequate solution in conditions of the uncertainty of optimal solutions [11].

3.7. Forecasting in energy engineering

3.7.1 Kinds of forecast

A forecast is the process of prediction resulting from logic premises and based on actual input data characterised by a high degree of probability in its realisation and concerning a defined horizontal time [9]. The probability may be defined conditionally or unconditionally. Due to the fact, that most input data are indeterministic, as a result of their processing an area of probable realisation arises in the forecast.

Planning the development of energy systems, concerning also the development of complex buildings, belongs to long-term forecasting. Planning the exploitation of energy systems is the area of short-term forecasting.

Forecasting the system consists in the probabilistic determination of the predicted value at the time imposed by the range of forecasting, based on the known history of the system

(statistically preset realisation in the time preceding the forecast). Energy forecasting is a probabilistic assessment of the value concerning the demand of energy and power (flux of energy).

The forecast is realised by means of prognosticating, which procedure includes mathematical, logical and heuristic elements. The input to this prognostication is information gathered by observing the predicted quantity obtained in the past and up to the moment of forecasting. The output of the procedure is a forecast of the future state of the quantity being considered.

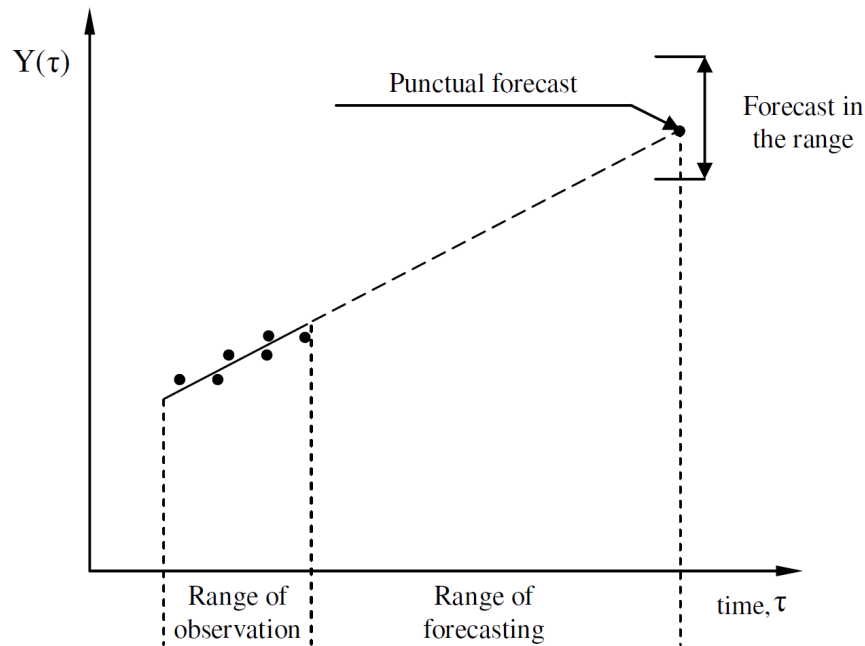


Fig. 3.3. Forecasting by means of extrapolation of the time trend

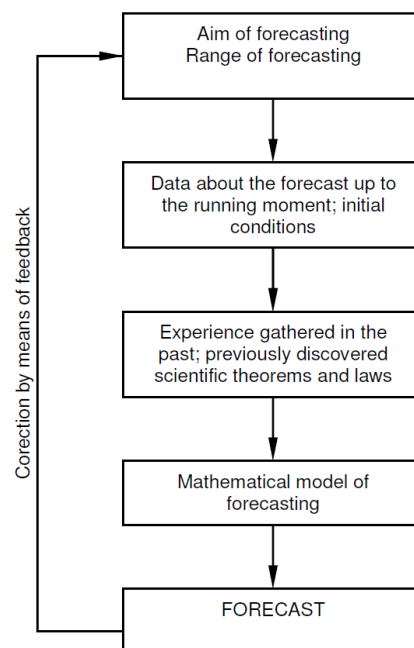


Fig. 3.4. Diagram of the structure of forecasting

Figure 3.3 illustrates a simple case of forecasting based on extrapolation of the time trend. Both a punctual forecast and a forecast in the range of assumed probability are presented. In Figure 3.4 a structural diagram of forecasting is shown [9]. Forecasting is based on information gathered in the past concerning the prognosticated quantity. This information ought to permit general regularities to be found and a mathematical model of the forecast concerning the investigated quantity to be constructed. Treated as a feedback, the results of forecasting permit a simultaneous correction of the procedure of prognostication.

The aim of forecasting depends first of all on the range of prognosticating depending on which the following kinds of forecast can be distinguished:

- a) current forecasting (six to 24 hours), which serves to optimise the exploitation of energy units including the optimal distribution of the load and determination of the graphic schedule of running repairs; of essential importance are the mean hour values of the demand for power (flux of energy); changes in meteorological parameters and in the influence of TV programs on the demand for power may be taken into account; current forecasting realised in the course of six hours permits to current control of the operation of the system and adjustment of the value of the demand for power.
- b) short-time forecast (three months to one year); of essential importance are the values of characteristic loads for all the days within the range of forecasting; the results of forecasting are plans for the production of energy carriers; shorter ranges of time (24 hours to three months) are connected with a correction of the plan for exploitation,
- c) medium-time forecast (one to ten years) connected with the cycles of realising investments in energy systems; the application of the proper methods in short-time or long-time forecasting depends on whether information is available about the increase of physical indices, whether the prices of the products have been stabilised, and whether possible changes in the prices can be predicted; of essential importance is information concerning the monthly demand for energy, the average and extreme monthly values for power in a typical 24 hours period; the correction for investment plans for energy-generating plants, planning of repairs, and international cooperation,
- d) long-time forecasting –ten to 15 (25 years) is connected with the life-time of the main energy units and with the demographic cycle (25 years); in this a case detailed data concerning the physical values of various equations are not available; thus we may base the forecast on macroeconomic quantities and international comparisons; of essential importance is the global demand for energy carriers, maximum annual power (energy flux), and the duration curve; the aim is to plan investments concerning fuel and energy-generating plants.

Mathematical models of forecasting may be divided analogically to input information in the systems into:

- deterministic models,
- probabilistic models with a known probability distribution of the random variable,
- incomplete probabilistic models with a known class of the probability distribution,
- models constructed according to the conditions of complete uncertainty of the input data.

The necessity of including the predicted results of DSM (Demand Side Management) in the assessment of future demands, shifts practical application from the classic methods of forecasting based on models of development trends (the method of extrapolating the trends, econometric method) towards the development of so-called technical-economic models (end-use).

In recent years attempts have been made in forecasting to apply the following methods:

- expert method,
- fuzzy systems,
- artificial neural network,
- hybrid system.

Practically, however, in energy engineering forecasting bases on the following three groups of models:

- extrapolating the trends,
- econometric methods,
- end-use model.

3.7.2. Methods of forecasting

3.7.2.1. Method of extrapolating the trends

This method is based on the treatment of data gathered in the past as a chronological series constituting the base for approximation and further on to extrapolation. The only independent variable synthesising the effect of various vectors on the predicted quantity is time. This method can be applied in the case of rather short ranges of time, assuming that future conditions will not differ much from those in the past. Simple extrapolation may be used for the purpose of predicting phenomena of an evolutionary character, moderately changing in time. If the phenomenon is characterised by stepwise changes, forecasting by simple extrapolation is not feasible. It should be neither applied in systems nor in processes without retrospective statistical data.

Forecasting by means of extrapolation composes the following stages:

- a) collecting and processing data from the past,
- b) choice and motivation in using the given mathematical model,
- c) processing statistical data to determine unknown parameters of the model,
- d) prognostication proper.

Statistical data must be deprived of the effect of accidental disturbances which counterfeit the correct values of the predicted quantity. The choice of the proper approximating function (trend function) decides the accuracy of the forecast. The best results of extrapolation are achieved when the approximating function ensues from theoretical premises or observations of similar phenomena and processes. The specifics of the investigated phenomenon should indicate whether the approximated function increases or decreases monotonically, whether it possesses an asymptote, extreme values or inflexion points, and whether it is a symmetrical or asymmetrical function. In the case of simple extrapolation the mathematical model of the predicted quantity is generally expressed as:

$$y = f(a, \tau) + z, \quad (3.5)$$

where:

y – forecast value,

a – vector of the parameters of the approximating function,
 τ - time,
 z – random term (taking into account disturbances), for which the expected value is equal zero.

The most frequent forms of the approximating function are:

- linear dependence

$$y = a_0 + a_1 \tau, \quad (3.6)$$

- power polynomial

$$y = \sum_{i=0}^n a_i \tau^i, \quad (3.7)$$

- exponential function

$$y = a_0 a_1^\tau, \quad (3.8)$$

- logistic function

$$y = \frac{a_0}{1 + a_1 a_2^{-\tau}}, \quad (3.9)$$

The analysis also comprises the derivatives of the trend function:

- simple derivative

$$\frac{dy}{d\tau} \cong \frac{\Delta y}{\Delta \tau} \quad (3.10)$$

- logarithmic derivative (characterising the dynamics of the factor)

$$\frac{1}{y} \frac{dy}{d\tau} \cong \frac{1}{y} \frac{\Delta y}{\Delta \tau} \quad (3.11)$$

- flexibility of the function

$$\frac{d(\lg y)}{d(\lg \tau)} \cong \frac{\Delta \lg y}{\Delta \lg \tau} \quad (3.12)$$

For the purpose principally of determining the unknown coefficients of the trend function, the least squares adjustment method is usually used. In the choice of the coefficients of the trend function, historically earlier statistical data should be treated as having less weight than recent data. If there are any premises indicating changes in the effect in the predicted system or process, it is expedient to ascribe the highest weight to the newest data rejecting the older data or to ascribing them less weight.

The accuracy of the forecast depends on the applied mathematical model of forecasting. Therefore, the procedure of forecasting ought to provide the possibility of correcting the form of the model based on the newest statistical data.

The method of simple extrapolation reducing the prognostication to a function of only one variable (time) is a considerable simplification of the reality. Also the assumption of continuing only quantitative changes in future, neglecting qualitative ones, is a fundamental drawback of this method, as well as the free choice in the horizontal time for the purpose of extrapolation.

According to [9] extrapolation of time trends does not provide satisfying results in the case of energy forecasting, due to too many essential effects which cannot be expressed by means of the time trend. These are changes in the dynamics of the growth of production, global product and in the structure of getting and distributing GDP, (e.g., on the level of consumption), and in the share of investments and export. Experience from the application of models extrapolating the trends permits the following conclusions to be formulated [9]:

- it is necessary to exclude the periodical component (periodical variability in the course of many years resulting from favourable or unfavourable economic situations),
- periods with extraordinary events require corrections of input data,
- in the case of stepwise changes being turning points in long-term trends the importance of data in preceding periods must be corrected; an example may be the sudden rise of prices for hydrocarbon fuels in the years 1973/74 (the so-called first energy crisis),
- circumspection is inevitable in drawing conclusions about systems in which sporadic changes in the demands are considerable in relation to the maximum power rating of the system.

3.7.2.2. Econometric methods

These are the most often applied methods of long-term forecasting in energy systems. In concrete applications they differ in the complexity of the applied model from the simple correlation of demands, depending on the index of industrial production or GDP up to multi-dimensional stochastic models, taking into account numerous factors connected with demography, economics and social policy. These methods of forecasting are also based on extrapolation expressed by transposition of relations existing in the past for the future. An adequate choice of independent variables ought to facilitate correct forecasting in conditions of the expected technological and economic development [9].

The regression function determines the character of the correlating connections between the consumption of energy and the fundamental indices of economic development, treated as random variables. In this way we can determine the energy forecast for various variants in the economic development and assess the correction of forecasting in compliance with changes in the assumed economic indices. For this purpose simple methods are applied in which the regression function includes only one independent variable and more complex methods of multiple regression.

The simplest econometric models apply only one independent variable, namely GDP, assuming that economic activity brings about demands for energy. More complex economic

models, take into account specific industrial activities, services (complex buildings), the behaviour of the consumers, and their energy effects, applying multiple regression.

Among the socio-economic, technical and geographical factors that affect the energy intensity, i.e., the ratio of energy consumption to GDP, we may distinguish:

- economic structure,
- applied energy techniques,
- geographical and climatic conditions,
- degree of energy self-sufficiency,
- ways of life.

The energy crises in the 1970s have caused that in economic models the prices of energy carriers are nowadays taken into consideration. Most frequently applied is now the econometric model in which the demand for energy is correlated with GDP and the price of energy carriers, where the exponents in the empirical formula are coefficients of elasticity GDP and energy prices (i.e. the ratio of relative increment of the demand for energy to the relative increment of GDP and energy prices) [9].

3.7.2.3. Method of heuristic extrapolation

This method is applied when the forecast cannot be achieved by means of more accurate methods. It consists of a set of logical and mathematically statistical procedures, the aim of which is to obtain information from experts. The information is then analysed and generalised in order to achieve the required forecast. An advantage of this method is the possibility of avoiding gross errors, particularly in the case of stepwise changes in the predicted quantities. On the other hand this method is characterised by subjectivity due to the subjective assessment by the experts. As the problem is rather complex and in order to avoid subjective assessment, a group of experts usually authorises the evaluation which ensures a better reliability. Besides, such an evaluation will include more risky solutions, and within the range of the assessments of the experts the proper solution should be found.

In order to attain a collective evaluation by several experts the delphic method ought to be applied. This is an iterative method of considering the opinions of a group of experts respecting their anonymity thanks to the application of special inquiries. Several rounds of inquiries are carried out, their results being processed and rendered accessible to the experts before to the next round. In this way a controlled feedback is realised which decreases the influence of the experts' individual or group interest, which might otherwise mar the objectivity of the forecast.

Besides its undeniable advantages, this method displays also has some drawbacks. These are first of all strenuous iterative researches, based on intuition and the subjectivity of the experts, as well as a directly proportional dependence of the quality of evaluation on the qualification of the experts.

3.7.2.4. Method of “end use” analysis

The „end-use” model was preceded by the method called „branch balances”. In this method the demand for fuels, electricity and heat is calculated by summing up the demand for energy by various groups of consumers or branches of the economy of the given country. All the energy carriers are reduced to the level of primary energy, taking into account the efficiencies of the chain of thermodynamic processes from primary energy to the final energy carriers.

The “end-use” models applied in various countries have a common basis, viz.:

- detailed information about the demand for energy on the level of the branch of the economy of the given country e.g., steel, cement and other semiproducts, as well as final users (e.g., complex buildings),
- scenario approach taking into account all the factors that influence the demand for energy.

The total demand for energy is calculated by aggregating the partial demands starting from the level of effective energy (lighting, heating and others) including the level of final energy (mainly electricity and heat) up to that of primary energy (non-renewable and renewable). Such a model requires, therefore, an accurate scenario describing future changes in technology, the economic and social development, the structure of municipal energy engineering (including complex buildings), and the structure of industry.

In these models prices of energy carriers are not taken into account directly, but their influence is included in the assumptions concerning saving and substitution of energy carriers. This is realised thanks to the introduction of simulation procedures concerning the behaviour of the investor-consumers or other decision-makers in the range of energy saving and substitution of energy carriers into the end-use models.

In the end-use model the choice of the proper level of aggregation is of essential importance. The identification of categories of consumers is inevitable in applying this model. Categories which prove to be most essential in the total demand for energy ought to be treated separately whereas less important categories may be treated jointly. The second important process in the end-use model is the formulation of the scenario. Three stages are to be distinguished:

- description of the social and economic environment in which the processes connected with the consumption of energy take place,
- quantification of the scenario variables,
- checking of the compatibility.

In the quantification stage, among other things, the possible range of the value of each variable in the future is assessed and for each scenario the most probable value of each scenario variable is determined. The compatibility of the whole scenario must be checked from the economic, political and technical points of view.

The end-use model may be applied jointly with the econometric model to form a hybrid model. Alternative methods that make use of new calculation techniques such as artificial neural networks, are justified where there are unsatisfactory sources of information and a considerable instability in the investigated processes [9].

The author of the paper [7] recommends two models: the econometric model and the “end-use” model in the case of long-term forecasting. This does not exclude, however, the application of the trend extrapolation method, although it must be stressed, that extrapolation should not reach too far into the future.

3.8. Criteria of optimisation and restrictions in the development of energy systems

3.8.1. Criterion of economic effectiveness

The aim of the optimisation of energy systems is to find the most effective method of gaining, processing and consumption of energy carriers, the demand for which is determined by assumptions in energy policy. The criterion of optimisation is presently formulated in compliance with NPV (Net Present Value) recommended by the United Nations Industrial Development Organisation UNIDO, representing the predicted economic profit discounted for the year zero [1, 2]:

$$NPV = \sum_{t=0}^n a_t NCF_t \quad (3.13)$$

where

a_t – discount coefficient,

NCF_t – net cash flow in i-th year,

t – serial number of the calculated year.

The index a_t reduces the effects and expenditures connected with the operation of the system to a common time reference by discounting them to the year zero [1,14]. The discount calculus bases on the assumption that in the considered period the economy is developing according to the geometrical series, warranting increase of the final production at a constant rate [4,15]. Thus the expenditures for construction and exploitation render effects that increase in the following years according to the geometrical series. The rate of interest of this increase is called discount rate, denoted by “ r ”. The discount calculus assumes that all the expenditures to be covered in the given year are conventionally paid at the end of each year. The operation of discounting is also called actualisation of economic values (for the given year or any given moment) [4].

If W_0 is a certain economic value spent in the year denoted by zero, in the successive years we get:

$$\begin{aligned} W_1 &= W_0 (1 + r) \\ W_2 &= W_0 (1 + r)^2 \\ &\dots\dots\dots \\ W_t &= W_0 (1 + r)^t \end{aligned} \quad (3.14),$$

Thus, the discount coefficient a_t for the year zero is expressed by the relation:

$$a_t = \frac{1}{(1 + r)^t}, \quad (3.15)$$

where r denotes the discount rate.

The interest rate results from the difference between the nominal interest rate and general inflation rate [14]:

$$r = \frac{r_c - r_i}{1 + r_i} \quad (3.16)$$

where:

r - discount rate,

r_c - interest rate of gaining the investment capital,

r_i - general inflation rate.

The achievement of a positive NPV value (Eq. 3.13) indicates that the investment is financially justified. The invested capital ensures a higher income than in the case of income resulting from investment on the capital market.

The profitability is also indicated by the so-called Internal Rate of Return (IRR), which expresses the limiting value of the rate of interest when the NPV is equal to zero:

$$\sum_{t=0}^n \frac{NCF_t}{(1 + IRR)^t} = 0 \quad (3.17)$$

If the investment is to be profitable the following inequality must be satisfied:

$$IRR > r \quad (3.18)$$

The choice of the proper discount rate for the national economy results from macroeconomic premises. If the discount rates are small, investigations requiring large expenditures are preferred. This may soon lead to a depletion of investment resources accompanied by an incomplete employment of human resources. If the values of the discount rate are too high, the opposite is the case, i.e., it leads to savings of investment resources and increased engagement of human resources.

If the annual value of production is assumed to be a constant average level, the minimisation of the annual mean total cost of production may be assumed as the objective function. The total annual costs are divided into fixed annual costs, independent of the amount of production, and variable annual costs depending on the amount of production:

$$C_a = C_{af} + C_{av} \quad (3.19)$$

where:

C_a - total annual costs,

C_{af} - fixed annual costs,

C_{av} - variable annual costs.

The annual fixed costs result from the equation:

$$C_{af} = \rho I + C_f \quad (3.20)$$

where:

ρ - annual capital recovery factor (factor of fixed costs),

I - capital expenditures,

C_f - component of fixed costs independent of capital expenditures.

The annual variable costs are calculated by means of the relation:

$$C_{av} = C_{ie} + C_l + C_{mr} + C_{rm} + C_{am} + C_{en} \quad (3.21)$$

where:

C_{ie} - cost of input energy,

C_l - cost of labour,

C_{mr} - cost of maintenance and repairs,

C_{rm} - cost of non-energy raw materials,

C_{am} - costs of auxiliary materials,

C_{en} - costs of detriments in the environment.

Incomplete input information does not allow unequivocal solutions to be achieved in the case of large energy systems and leads in practice to similarly effective economic solutions corresponding to various investment expenditures. In this case an additional criterion must be introduced, not contradicting the principal criterion, such as reliability if it is not a component of the main economic criterion.

The minimum consumption of fuel, minimum losses of voltage in the power grids, and the maximum reliability, sometimes applied as separate criteria, usually yield erroneous results. Generally, this is equivalent to assuming that the best variant is the variant with the highest investment expenditures, no matter how high the achieved economic effect may be [11012]. There are, however, some exceptions. For example in the case of energy devices in space missiles, the fundamental criterion of optimisation may be the minimum weight or maximum reliability.

3.8.2. Criterion of social effectiveness (quality of life) [6]

The pertinence of the merely economic criterion is often contested because it does not taken into account factors which are difficult to measure and cannot even be fully expressed in monetary units but may be decisive for the quality of life of people. Accepting quality of life as an optimising criterion is equivalent to accepting social effectiveness as superior to economic effectiveness. The notion “quality of life” comprises such factors as pastime, freedom to choose one’s job and place of work, as well as dwelling, the ability to make decisions, the right to creativity, the right to enjoy fresh air, pure water, silence and so on [6]. The influence of energy systems on quality of life may be either positive or negative. The latter includes hazards to the natural environment. Positive effects include raising the efficiency of common transport, labour-saving devices, improvement in the comfort of housing, and automation of work in industry and agriculture.

Quality of life is assessed in compliance with the following components: economic, political, ecological, social, state of health and education [6]. The psychological factor is not taken into account because it cannot be assessed quantitatively.

The economic component includes:

- income per person,
- economic conditions of the given region with respect to the concentration of economy, the quantity of production, investments of money in the banks, the level of pauperisation, inequality of income, and percentage of unemployment.

The political component comprises the following factors:

- degree of providing the society with information and the percentage of people involved in political activities,
- assessment of the activities of local authorities concerning the state of people's health, level of education, and criminality,
- degree of charitable activities.

To the ecological component belong:

- pollution of air, water and soil,
- the level of noise,
- natural state of the environment determined by the frequency of changes in weather, and the number of sunny days and days with unfavourable weather conditions,
- possibility of recreation.

The social component includes:

- possibility of earning money,
- number of working hours,
- index of education,
- possibility of selecting and obtaining information (edition of newspapers and magazines),
- density of population,
- equality of race, sex and place of dwelling,
- general living conditions,
- possibility of recreation and services,
- pastime,
- number of libraries, cultural and sports facilities.

The state of health is assessed according to the following factors:

- death rate among children and the whole society,
- percentage of people unable to work due to chronic diseases,
- medical services.

Concerning the state of education the following factors are to be taken into account:

- possibility of education,
- index of average marks in selected subjects (e.g., mother tongue, and mathematics) at the finishing level of secondary school education,
- percentage of young people finishing schools without having to repeat.

The criterion of the quality of life also includes indices about the level of science and art. This concerns the number of scientists dealing with fundamental researches and the number of professionally active artists.

The practical application of the criterion of the quality of life requires the determination of factors affecting the standard of life. The "Stanford-PILOT" model [5] quotes the criterion based on social effectivity.

3.8.3. Restrictions in the development of energy systems

The basic restrictions in the development of energy systems are [10]:

- availability of human resources,
- restrictions in transport,
- limited water resources,

- protection of the natural environment,
- availability of sites,
- availability of raw materials and fossil fuels,
- restrictions in the domain of export and import,
- investment expenditures.

Demography forecasting provides input information for the scenario of development of the energy system, which is connected with the increase of electricity consumption and also partly the automation of industry, agriculture, transport and services reducing the demand for human resources. The balance of human resources is essentially influenced by the structure of the energy balance. The number of people employed at installations fired with solid fuels is several times higher at installations fired with liquid and gaseous fuels or fed with electrical energy. The availability of human resources particularly affects the development of the subsystem that deals with gaining solid fuels.

The electro-energy system consumes considerable amounts of water for cooling in condensers. The consumption of water in conventional power stations amounts to 120 to 150 m³/MWh. A nuclear power station needs 30 to 50 per cent more water than conventional power stations [3]. Irreclaimable losses of water (due to evaporation) amount, depending on the kind of the cooling cycle, to:

- open river cycles - 0.2 ÷ 0.3 m³/MWh,
- open reservoir cycles - 0.8 ÷ 0.9 m³/MWh,
- closed cycles - 1 ÷ 1.5 m³/MWh.

The preheating of water by eight to 11K in open cooling cycles deteriorates biological life in rivers and water reservoirs. An increase in temperature decreases the level of oxygen in the water and hampers the development of microorganisms, the presence of which is indispensable for purifying water from noxious microbes (the level of oxygen in the water must exceed 5mg/l). The power rating of power stations situated on river banks is limited due to an admissible increase in the temperature of water in a river with a low water level.

An interesting solution consists in mixed cooling cycles. These are open cycles with attached ventilating cooling towers. If the hydrological conditions are favourable, the power station operates in an open cycle, and if the water level is low, a part of the power station is switched over to run in closed cycles. The costs of such an operation are then intermediate between open and closed cycles.

When power stations with open or mixed cycles cannot be constructed, more power stations with closed cycles must be set up. The limit is the admissible loss of water due to evaporation. Such cooling cycles are comparatively expensive, with respect to both investments and their exploitation. They also cause the highest losses of water. Cooling towers cause fogs affecting the microclimate.

In future in the development of electro-energy subsystems dry closed cooling cycles may be taken into account. The water is cooled down in a closed installation. It flows through ribbed tubes which transfer heat through their walls. As an investment such a solution is most expensive but it does not affect negatively the water economy of the region.

Large strip mines involve the formation of depression craters bringing about a lowering of the underground water level. This affects vegetation and requires the construction of water pipe networks in order to provide water for households.

The consumption of fossil fuels is connected with the emission of noxious substances, mainly dust, sulphur, nitrogen and carbon oxides. Nitrogen oxides usually occur together with sulphur oxides. They result in the formation of nitric and sulphuric acids, increasing the corrosion of metals. Carbon oxide leads to changes in human blood, as well as irreversible changes in the whole organism. Dust decreases solar radiation and hampers photosynthesis.

An increased share of carbon dioxide in the atmosphere may disturb the equilibrium of the radiation at the surface of our globe, because carbon dioxide absorbs infrared radiation emitted by the Earth's surface, resulting in an increase in atmospheric temperature (the so-called greenhouse effect). An excessive increase in the average temperature of the atmosphere may lead to catastrophic changes in the climate (melting of polar ice, a higher water level of the oceans, and a shift of climatic zones northward). It must be kept in mind that the difference in the mean temperature between the present era and the glacial epoch amounts to only five degrees.

The problem of dustiness can be effectively solved by keeping up a guaranteed efficiency at the level of 99 per cent of electro-filters. The emission of very fine dust (below $20\mu\text{m}$), is particularly harmful. It cannot be caught by electrofilters but remains in the atmosphere for a long time, and the human organism has no successful natural protection against it. Power stations also contribute to the degradation of the natural environment by dumping ashes. Solid wastes may be partly utilised in the production of building materials.

The transmission of electricity by means of overhead power grids creates an electrostatic field which negatively affects both people and animals. In order to decrease the intensity of the electrostatic field on the Earth's surface higher electric poles must be constructed. This situation may be improved by applying cable grids. The application of such cables and hermetic electric stations will prove to be necessary as that electro-energy systems occupy more and more space.

The operation of nuclear power stations gives rise to the transfer of heat to the environment and radiative contamination of water and air. The latter is also caused by those industrial plants which take part in the nuclear fuel cycle and the transport of fuel and wastes. On the other hand nuclear energy engineering does not involve directly dustiness of the atmosphere and emissions of noxious sulphur and nitrogen oxides. There are no sludge and ash dumps [3]. The site of a nuclear power station is smaller than that of a conventional power station. It ought to be stressed that a nuclear power station is characterised by direct zero carbon dioxide emission.

The development of an electro-energy subsystem requires new sites for the construction of power stations, distribution stations of high- and medium-voltage electricity, as well as poles for overhead power grid. An increased share of cable lines in the electrical grid decisively decreases the area available for housing. Cable grids are, however, many times more expensive than overhead grids.

3.9. The choice of a solution in conditions of indefinable optimal solutions

Due to the uncertainty of input data and the economic stability of solving any given energy problem, an area of indefinability of optimal solutions does arise [11,14]. This requires the application of an adequate procedure for optimisation. The uncertainty of input data is caused by external and internal factors. The external factors comprise geophysical and social-economic factors, such as changes in the pace and direction of the economic development, new trends in technical progress, and changes in the price of raw materials and fuels. To the internal factors belong changes in the structure of energy systems, the efficiency and degree of reliability of installations, and changing conditions and structures for supplying energy carriers [14].

The procedure for solving the optimising problem in conditions of uncertain input data consists of the following five stages [11, 14]:

- I. Gathering sets of input data.

The aim of this stage is to choose the characteristic sets of input data. Having chosen the deterministic indices and statistic distributions of the remaining factors, an adequate number of sets of input data is chosen by sampling and applying the Monte Carlo method.

II. Determination of the optimal solution for each characteristic set of input data.

Based on engineering analysis for each set of input data, possible variants of technical solutions are chosen. Next, for each set of input data the optimal variant is selected based on deterministic optimisation.

III. Analysis of the economic effects of the operation of the chosen optimal variants with other values of the input data.

At this stage a mathematical model must be developed which permits to calculate the cost of adapting the given variant to changed conditions of operation. The aim of this stage is to set up the so-called strategic table of costs (Table 3.2). The columns in this table correspond to the respective characteristic sets of input data. The rows concern the optimised variants of the solutions corresponding to the respective sets of output data. In the main diagonal there are values of the objective function calculated in the former stage. The other items in this table result from calculations accomplished in stage III.

Table 3.2

Strategic table of annual costs

i \ j		Sets of input data					
		1	2	...	j	...	n
Technical solutions	1	$K_{R\ 11}$	$K_{R\ 12}$	...	$K_{R\ 1j}$	...	$K_{R\ 1n}$
	2	$K_{R\ 21}$	$K_{R\ 22}$	...	$K_{R\ 2j}$	...	$K_{R\ 2n}$
	...	...	...	...	...	...	...
	i	$K_{R\ i1}$	$K_{R\ i2}$	...	$K_{R\ ij}$	...	$K_{R\ in}$
	...	...	...	...	...	...	...
	n	$K_{R\ n1}$	$K_{R\ n2}$	...	$K_{R\ nj}$	...	$K_{R\ nn}$

IV. Choice of the group of best solutions with equivalent economic effects.

The aim of this stage is to choose from among the variants presented in Table 3.2 that group of with the least economic risk, in the case of changing values in the input data. Because of the lack of an explicit criterion various criteria are simultaneously applied.

Laplace's criterion:

$$K_R^{(1)} = \min_i \frac{1}{n} \sum_j K_{R\ ij} \quad (3.22)$$

where:

$K_{R\ ij}$ - annual cost of the i-th technical solution corresponding to the j-th set of input data,
n - number of optimal solutions or number of the set of input data.

Bayes' criterion:

$$K_R^{(2)} = \min_i \sum_j p_j K_{Rij}, \quad (3.23)$$

where p_j denotes the probability of the occurrence of the j -th set of input data.

Wald's criterion:

$$K_R^{(3)} = \min_i \left(\max_j K_{Rij} \right) \quad (3.24)$$

First for each solution the least convenient set of input data is chosen, and next a solution with the lowest pessimistically determined annual cost is found.

Hurwic's criterion:

$$K_R^{(4)} = \min_i \left(\lambda \max_j K_{Rij} + (\lambda - 1) \min_j K_{Rij} \right) \quad (3.25)$$

where λ denotes the coefficient of the statistical weight.

In this case, first the highest value of the annual cost is chosen for each solution corresponding to the sets of input data undergoing changes. Based on these values the weighted average value is calculated. If there is data lacking for the calculation of λ , the arithmetic mean may be calculated. Next, the best technical solution with the least average annual cost is chosen.

V. Heuristic analysis of the group of economically equal solutions.

The group of the economically best solutions obtained in the stage IV leads to the formation of an area of indefinability of optimal solutions. To make the final choice of the optimal solution, supplementing non-economic criteria are used. These may be, for instance:

- reliability, if not contained in the objective function,
- ability to adapt varying external conditions,
- influence on the environment, if not taken into account in the objective function,
- consumption of scarce materials,
- influence on employment,
- conditions of the military systems of the country,
- influence on international relations.

At this stage cooperation with experts representing the aforesaid branches is indispensable. Thus, the stage V like stage I, contains heuristic elements.

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Chapter 4

ENERGY MANAGEMENT OF COMPLEX BUILDINGS AS A SYSTEM

Energy management of complex buildings is a set of mutually connected energy branches (energy processes and installations) the aim of which is the production, transport and distribution of energy carriers to consumers (e.g. office rooms and garages). Due to these connections the energy management treated as a whole is characterised by features not displayed by particular energy branches considered separately [7]. Therefore, energy management of complex buildings can be considered as a system from the viewpoint of the oldest definition of system formulated by Aristotle [4].

Typical complex buildings are, among others, airports, hospitals, office buildings, sports and recreation buildings, and shopping centres. The centralised supply of complex buildings with final energy carriers (electricity and heat) is realised by the national electro-energy system and district heating systems. Centralised supply with final energy carriers is more and more often replaced by modern distributed energy systems. The application of distributed energy systems reduces losses due to the transmission and distribution of energy to consumers. Decentralised supply of heat and electricity is more often realised by small-scale cogeneration systems, which may be equipped with piston engines, microturbines, Stirling engines and fuel cells. Small-scale cogeneration systems may be connected to cooling installations realising the “trigeneration” technology (BCHP- building, cooling, heating and power). In modern distributed energy systems the application of renewable energy sources is increasing, mainly by solar energy (solar collectors and solar photovoltaics). Ground-sourced heat pumps are also applied.

4.1. System approach to energy analysis of complex buildings

Nowadays complex buildings are characterised by a large variety of energy requirements, which involves a complexity of energy management. The term “complex buildings” denotes one building or a set of buildings, the energy management of which is complicated (e.g. supermarkets, airports and recreation centres).

Final energy carriers (electricity and heat) are used in complex buildings to provide a variety of services, such as lighting, space heating, hot tap water production, space cooling,

refrigeration, dehumidification, and electricity for internal equipment. The production and consumption of energy carriers in complex buildings take place within a network of interconnected processes. In complex buildings the connections between the production and consumption of energy carriers mean that global energy management is more than the sum of energy processes considered separately. This last sentence, if not applied merely to energy, is the oldest definition of the system reaching back to Aristotle. Thus, the energy management of complex buildings is a system defined as a set of energy installations, devices and interconnections between them, as well as external connections with the environment. Due to these interconnections, energy management treated as a whole is characterised by features not displayed by its parts (the respective energy branches such as, for instance, hot tap water or a cooling agent).

Energy management of complex buildings considered as a large energy system belongs to continuously developing artificial hierarchical systems, in which people are organically connected with the controlling and controlled parts of the system. The energy subsystem of complex buildings displays features of both technical (cybernetic) and economic systems. The technical character of the energy subsystem results from the material and energy connections between the elements [12]. The activity of people in the controlling and controlled elements of the system determines its economic character.

A characteristic feature of the energy subsystem as an organised system is its hierarchical structure. This property consists in the fact that the respective elements of the energy subsystem (the respective branches producing energy carriers) are subsystems of a lower order, and the energy management as a whole is considered to be a system on a higher level. The energy management of complex building is characterised by its compactness due to pipe and grid connections. The energy subsystem decisively influences the activity of the subsystem of consumers, although its role is rather to serve them.

The hierarchical feature of the energy subsystem is applied in the preliminary design of the energy management in order to decompose the global task of optimisation for the choice of the optimal variant of the energy management structure in complex buildings.

The energy subsystem of complex buildings belongs to open systems exchanging materials, energy and information with the environment. Connections with the environment are external ones. Among external connections of the energy subsystem of complex buildings the following groups may be distinguished:

- connections between the energy subsystem of complex buildings with the national energy system,

- restrictions concerning capital expenditures, the supply of machines, materials, fuels and energy,
- connections with the natural environment.

External connections are characterised by inertia. This means that additional demands for energy carriers and energy installations and devices cannot be realised at once. Special attention should be paid to connections with the natural environment mostly due to negative ecological results.

Calling a building “an energy subsystem” means that such a structure is treated as a set of installations and devices whose task is to produce, process, transport and distribute the energy carriers required for the needs of complex buildings, and also a set of connections between these installations of various kinds such as heating, ventilating installations and air-conditioning, including small-scale CHP units. The connection of CHP units with cooling systems permits the so-called “trigeneration” technology to be realised [5]. Systems applying trigeneration in complex buildings are called building, cooling, heating and power (BCHP) systems. In such systems fuel cells may also be used. Such systems utilise natural non-renewable resources much more effectively.

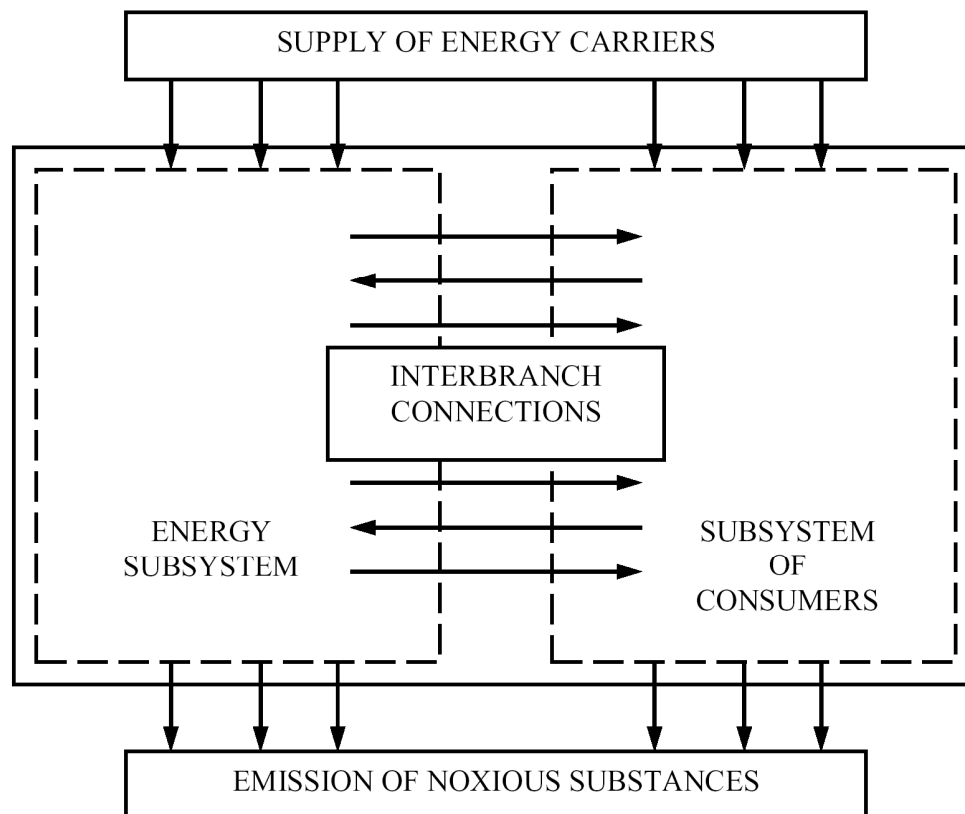


Fig.4.1. The concept of energy management of complex buildings as “an energy system”

The idea of the energy management of complex buildings as an energy system is presented in Figure 4.1. In the energy management of complex buildings characteristic subsystems are to be distinguished, viz., the energy subsystem (responsible for the production, processing, transport and distribution of the energy carriers inside the building) and the subsystem of energy consumers.

4.2. Examples of complex buildings

4.2.1. Airports

Modern airports consume much energy. In terminal buildings and non-passenger areas many installations and much energy equipment are used for heating, air-conditioning, dehumidification, cooling and power generation. Owing to air safety, airports are also equipped with backup power generation systems. Such complex buildings are characterised by high electricity consumption for a huge number of electrical devices. A significant amount of electricity is consumed for air traffic maintenance systems (radars and navigation systems, radio stations, aircraft service, and lighting systems on the runways and on aprons). The energy demand in airports depends on many various structural factors, e.g., thermal insulation of buildings, glazing ratio, infiltration, wall orientation, building height, construction materials and external cover systems.



Fig. 4.2. Airport terminal building –Brač Island, Croatia

In such complex buildings the energy demand also highly depends on operational factors, such as occupancy time during the day and seasonal fluctuations, number of passengers and workers, area of air-conditioned spaces, heat gains from process equipment, and so on. A huge amount of energy in such buildings is consumed by facilities usually placed within the airport area, such as luggage stores, shopping centres, restaurants and so on. The demand for heating and cooling in such facilities is closely related to the geographical situation of the airport and external meteorological conditions. The simultaneous demand for heating, electricity and cooling provides an opportunity to apply CHP units instead of traditional heating systems in such complex buildings [3]. CHP units may be connected with the production of cooling agents, particularly in absorption chillers, forming the trigeneration systems.

4.1.2. Hospitals

Hospitals are characterised by unique and high energy consumption requirements. Such buildings require heating and lighting 24 hours each day, and a huge amount of energy for air-conditioning, ventilation, sterilisation, compressed air installation, laundries, food preparation and other equipment. In hospitals heat is delivered to consumers in the form of hot water or steam. Steam is also used in sterilisation and humidification systems. Due to the large number of occupants, hospitals are characterised by high hot tap water consumption. Electricity is used in many types of installations and equipment in hospitals. The highest demand for electricity occurs in the following installations: the lighting system, the air-conditioning system, compressors of process air, water-circulating pumps, special medical equipment (diagnosis and treatment devices), and standard office equipment.

Usually there are two types of compressed air installations in hospitals, viz., technical and medical air. A technical installation does not concern the patients and is used for pneumatic control systems and other technical purposes. Medical compressed air is a high-quality medium, used for the care and treatment of patients. It is supplied in the medical breathing equipment and in medical tools powered by compressed air.

Cold plays an important role in hospitals. In most cases the cold is transported using installations of ice water. The internal climate (temperature and humidity of ventilation air) must be controlled. Due to strict medical requirements, in some rooms (operating theatres, diagnostic rooms) the internal air parameters have to be controlled very precisely. Large numbers of filters (mechanical, chemical and biological) lead to high electricity consumption

by the air-conditioning system in these rooms. Due to the high cooling demand, in many modern hospitals absorption chillers are used instead of traditional compressor refrigeration systems. Such chillers may be driven, among other things, by waste heat from CHP units based on microturbines or piston engines. More innovative projects in the energy management of hospitals suggest the application of fuel cells.

4.1.3. Office buildings

Office buildings are considerable energy consumers, mainly of electricity. In Europe office buildings consume annually 100 to 1000 kWh/m² [2]. The level of energy consumption depends, of course, on the location of the building, the time of operation during the day and the week, the construction of the building, internal equipment, applied energy installations and devices, the number of occupants, and so on.

The operation of such buildings is connected with a high energy demand for air-conditioning systems. In many cases the demands are covered by conventional heating, ventilation and air-conditioning (HVAC) systems, but in some modern buildings more and more often a concept of distributed environmental indoor climate control systems is realised. These systems supply conditioned air directly to individual office rooms or spaces [1].

Huge amounts of electricity are also consumed by internal office equipment, such as computers, printers, fax machines, copying machines, and so on. Usually offices are closed at night and during weekends, so that the office equipment is not used at that time. Often the electrical devices are in a standby mode at that time, consuming only a small amount of electricity. It is possible to reduce this electricity consumption in offices by switching off unused devices.

Due to the cyclic demand for energy carriers in office buildings, various accumulative systems of heat and cold may turn out to be profitable. CHP or trigeneration units in such buildings are often equipped with storage tanks for heating or cooling media. The application of storage tanks allows the load to be equalised and makes it possible to operate the heating and cooling installations in a more efficient load range. Such accumulative systems may also be realised in a passive way, e.g., by applying natural night cooling ventilation.



Fig. 4.3. Modern office building

4.1.4. Sports and recreation buildings

Sports and recreation buildings (e.g. swimming pools, sports halls and ice rinks) are structures with unique energy demands.

Swimming pools consume a huge amount of energy for heating the pool water to an adequate temperature. Due to the required high internal temperature, energy consumption for space heating is also significant. This is why heat recovery systems are applied in such structures to save energy. Due to water evaporation from the pool surface a dehumidification system is often applied. The dehumidification system controls the humidity in an indoor swimming pool in order to ensure thermal comfort and avoid condensation on cold surfaces. Released moisture includes some chlorine or bromine disinfectants. Such compounds may be harmful (mainly due to corrosion) to the equipment that remains in contact with them.

Sports halls are characterised by a huge cubature and involve special heating systems. Thermal comfort in sports halls is one of the most important decisive factors in a heating installation. One of the ways to ensure this comfort is to apply radiant ceiling panels. In this case the radiant panels are a very energy-effective way to keep the internal temperature at a suitable level. An appropriate air-conditioning system in sports halls is also a real challenge. Very often during sporting events the halls are full of people. Their numbers inside the hall determines the level of air change. In most cases such structures involve a large-load air-conditioning system, so that its efficiency is crucial to the overall energy balance of such buildings. Sports halls also consume a huge amount of electricity for lighting.

Keeping an ice rink in operation is, of course, connected to a huge energy consumption for cooling. In most cases compressor refrigeration systems are used. The application of compressor refrigerators facilitates the control of the ice cooling process, but due to electricity used as a driving force it is quite expensive. The demand for heat in the building or in its vicinity permits CHP units with absorption systems (trigeneration technology) to be applied. Good quality ice involves suitable humidity of the internal air.



Fig. 4.4. Water park building

4.1.5. Shopping centres

Shopping centres are often large and complex structures. Such complexes may include shops, cinemas, restaurants, laundries and car parks. Energy requirements for these spaces are quite

different. The control of indoor air parameters, the supply of outdoor air, the management of exhaust gases, refrigeration requirements, and heat removal systems are only some of the problems in the energy management of such complex buildings. In most cases the central heating or central air-conditioning system is insufficient for all spaces. This is a concern for small individual shops, sometimes using individual air-conditioning systems. In most large shopping centres there are also food storage areas, which require reliable cooling media at several temperature levels. This is why such complexes often have their own backup power system. The energy consumption in shopping centres varies during the day and the week, which requires the application of heat and cold storage systems.



Fig. 4.5. Shopping centre

4.2. Modern distributed energy systems in complex buildings

Modern complex buildings such as office buildings, hospitals, supermarkets, hotels and so on, demand a rich set of different energy carriers to achieve thermal comfort and cover the process needs. Rising standards of rational energy utilisation require the application of new devices and technologies in such buildings. In recent years new trends in the field of energy production by distributed energy systems in complex buildings have arisen. Distributed energy production, also called decentralised generation or on-site generation, involves energy production by many small energy systems, like small-scale combined heat and power (CHP)

units, fuel cells, trigeneration technology and so on. The concept of this idea is presented in Figure 4.6.

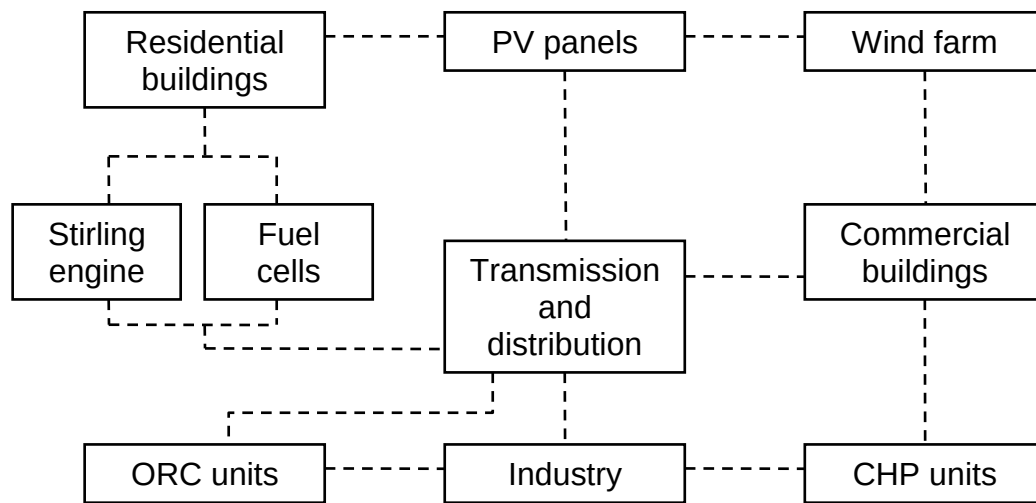


Fig. 4.6. Concept of the distributed power system

A typical power generation system needs a central power unit. Usually this is a large power plant, heating plant or CHP plant, connected to high-voltage grids and heat distribution networks. The operation of such a system generates losses in energy transmission and distribution to consumers. The application of distributed energy systems reduces these losses, because energy carriers are produced close to the consumers, in many cases inside the complex buildings. Such a solution reduces the number and size of distribution networks that must be constructed.

4.2.1. Small-scale cogeneration systems for application in buildings

Energy production in the cogeneration process

Heat and electricity are the basic final energy carriers consumed in complex buildings. Therefore, from the economic and ecological points of view their production should be realised in an optimal way. Separate production of electricity and heat from fuels is a thermodynamically less effective process. One of the best solutions to be applied in buildings is combined heat and power production (cogeneration). Cogeneration is the simultaneous generation of two different forms of useful energy, using one energy source. The process permits a high overall thermal efficiency to be achieved in comparison with separate energy production. The most common cogeneration process in modern buildings is CHP generation.

Although a small-scale cogeneration plant may only have an electrical efficiency of about 30 per cent, which is less than that of a typical power station, the ability to use waste heat makes it definitely more energy efficient. CHP plants can operate with an energy efficiency of up to 90 per cent and even higher if they are fed with natural gas. This leads to lower operational costs and lower environmental damages. Figure 4.7 shows the energy effects of the cogeneration process. The left chart in Figure 4.7 shows the energy input and output in the case of separate heat and electricity production. The right one presents the energy flows in a small-scale cogeneration plant.

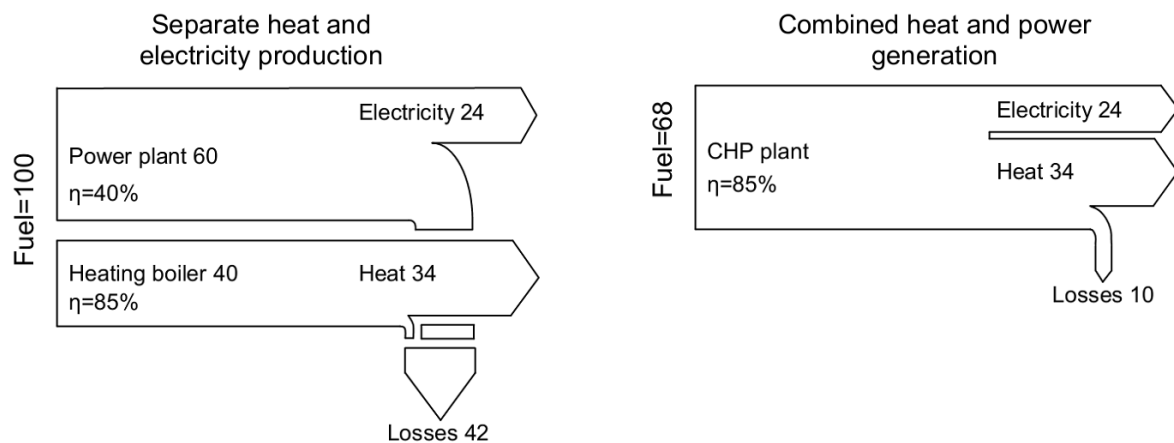


Fig. 4.7. Flow chart comparing separate heat and electricity production with a small-scale CHP plant; η - energy efficiency

In order to apply a small-scale CHP unit efficiently in complex buildings the heat and electricity demand must occur simultaneously during a specified number of hours over the whole year [8]. Meeting this requirement determines whether the investment achieves a positive economic effect. The positive effect results from the replacement of heat and electricity produced in central plants by the local production of these energy carriers in a CHP unit installed inside the complex building.

Combined heat and power (CHP) units based on piston engines

In general, two basic types of piston engines are used for power generation: the spark-ignition engine and the diesel engine. These units can be started up in a very short time; that is, in less than a dozen seconds or so. Spark-ignition engines are environmentally more

friendly than diesel engines but less efficient. The energy efficiency of spark-ignition engines reaches 43 per cent while diesels can achieve nearly 50 per cent. The efficiency of diesel engines is rather stable when the load changes. At 50 per cent load the efficiency of a spark-ignition gas engine drops by 10 to 15 per cent. Because spark-ignition engines may be fed by natural gas they are more popular for power generation today. Power generation units based on piston engines are available in a wide range of sizes, from 1 kW to 70 MW.

Piston-engine-based CHP units are the most common small-scale cogeneration plants for application in buildings. CHP units realise a cogeneration process with low investment costs and a relatively high energy efficiency (even at low load). In such a plant the piston engine drives the generator where the electricity is produced. Heat is supplied by the cooling system of the engine from several heat sources at different temperatures. In most cases the heat is recovered from the following heat sources:

- water jacket,
- exhaust gases,
- lubrication system,
- turbosupercharger cooling system.

Most heat is recovered in the water jacket by hot water with a temperature of 80 to 90° C. Exhaust gases can provide hot water with a higher temperature, even close to 120° C. It requires an additional heat exchanger. After the heat exchanger the exhaust gas temperature is about 120° C. A further reduction of the exhaust gas temperature requires the application of condensing heat exchangers. Such a solution requires additional investment costs for the heat exchanger, but it is justified when the low temperature heating system (for example the floor heating system) is applied in the building. Usually heat is supplied to the heating systems by a hot water installation, but in particular cases steam can also be generated (e.g. in hospitals). A flowchart of a CHP unit based on the piston engine is presented in Figure 4.8. The diagram shows an exemplary configuration of the heat recovery system in the cycle. The estimated energy flow (Sankey diagram) for the typical CHP unit based on a piston engine is presented in Figure 4.9.

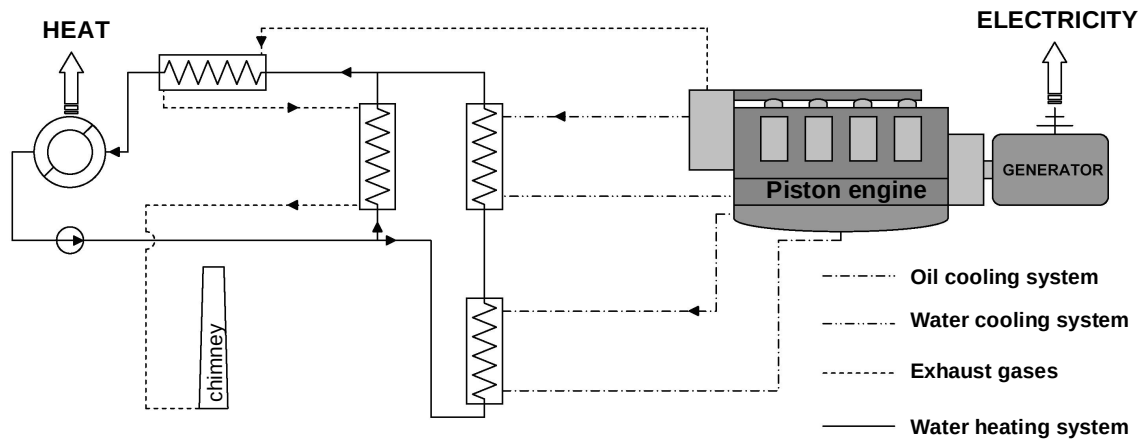


Figure 4.8. Heat sources in the piston engine based CHP unit

The operating speed of the engine depends on the size of the CHP unit. Smaller engines operate at higher speeds; larger ones at a lower speed. Usually the CHP unit is synchronised with an electricity grid which operates at a frequency of 50 or 60 Hz. This is why the operating speed of the engine must be adjusted to those frequencies. There are three piston engine classes:

- high speed, <3.5 MW, operating at an engine speed of 1000-3600 rpm,
- medium speed 1-35 MW, 275-1000 rpm,
- low speed 2-70 MW, 58-275 rpm.

The engine efficiency and power density (power output in relation to the engine capacity) depend on the speed of the engine. Generally, larger and slower engines operate with a higher efficiency, but the output power in relation to their size is rather low. High-speed engines are less efficient but supply more power output from the capacity unit.

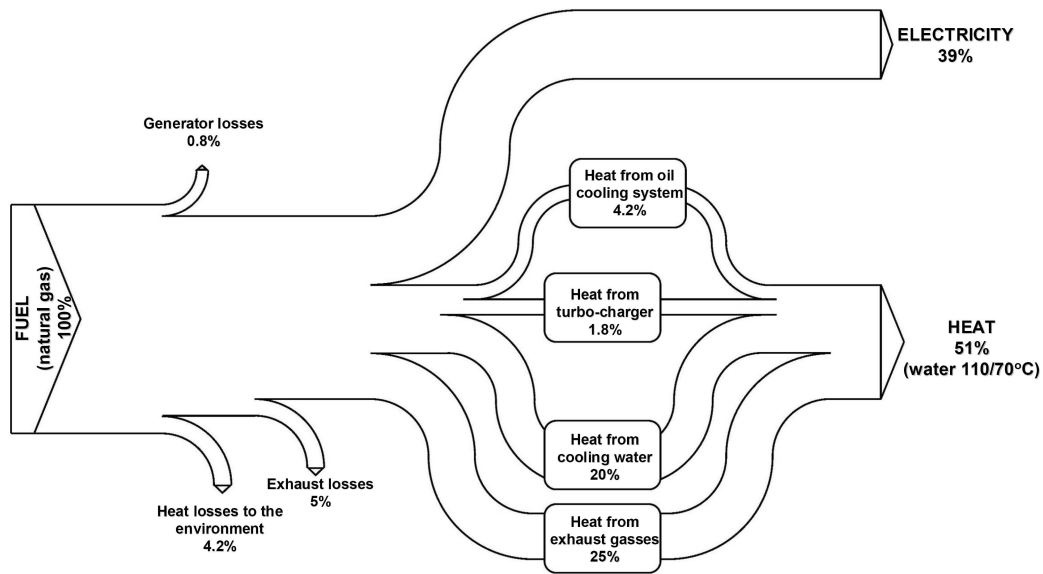


Fig. 4.9. Sankey diagram of energy flow in the CHP unit with a piston engine

CHP units with piston engines may be fed with the following fuels, among others:

- natural gas,
- LPG,
- biogases;
 - landfill gas,
 - gas from biomass gasification,
 - gas from sewage-treatment plants,
 - gas from biological fermentation,
- waste gases from industrial processes,
- diesel oil,
- liquid biofuels.

The operational costs of the CHP unit depend strongly on the type of fuel used. Waste gases, landfill gases and gases from sewage-treatment plants are usually low-cost fuels. This is why such units are more and more popular in places where waste fuel is available. However, a piston engine is dedicated to a specified range of fuel parameters, and their limits must not be exceeded. Some undesirable substances in the fuel may significantly shorten its lifetime.

At present there are many kinds and configurations of CHP plants with piston engines available on the market. For application in buildings the most popular CHP plants are fed with natural gas. Table 4.1 shows the properties of five commercially available CHP units. Piston-engine-based CHP units generate vibrations and noise. This is why in some applications, such as hospitals and hotels, efficient noise insulation is required.

Table 4.1. Energy performances of the exemplary commercial piston-engine-based CHP units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Electric power, kW	43	100	526	1063	5005
Electric efficiency, %	33.3	34.1	39.5	40.8	41.4
Heat production, kW	72	167	635	1190	6355
CHP ratio	0.6	0.6	0.83	0.89	0.79
Overall efficiency, %	89.1	90.1	87.1	86.4	94

Combined heat and power (CHP) units based on microturbines

Another way to produce heat and power in cogeneration for buildings is to apply gas microturbines in CHP units. In contradistinction to piston engines microturbines generate less vibration and noise. They operate with a higher ratio of power output to the size of the unit. In some power ranges the CHP unit with a microturbine is ten times lighter than the relevant unit based on a piston engine. There is no cooling system in CHP units with a microturbine. The only heat source is the heat exchanger recovering heat from exhaust gases. The block diagram of such a unit is presented in Figure 4.10.

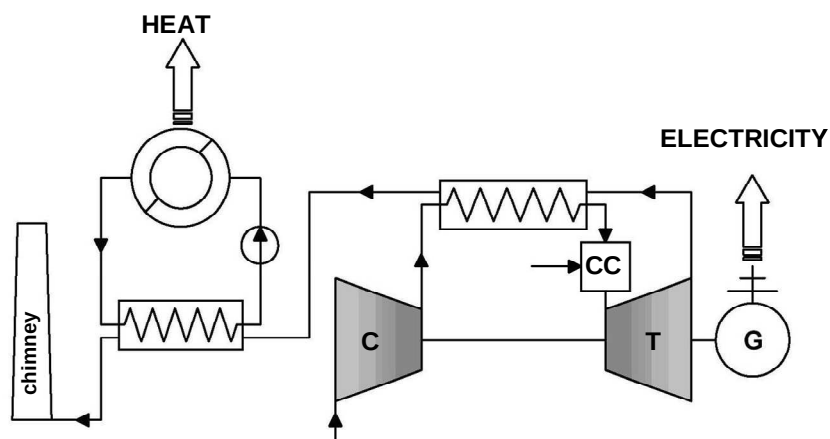


Fig. 4.10. Block diagram of microturbine based CHP units.

Microturbines are widely used to supply energy to complex buildings. Modern microturbines are characterised by their relatively simple construction. Therefore such units are distinguished by high availability in comparison with piston engines. In most cases microturbines are two-stage machines with a radial wheel. Presently on the market two types of microturbines are available: with or without internal heat recovery. In microturbines without internal heat recovery the air-fuel mixture burns in the combustion chamber, and the hot flux of flue gases expands in the turbine. The turbine drives the electrical generator. Such turbines operate in a simple thermodynamic cycle, and they are cheaper and more reliable than microturbines with internal heat recovery. These latter use a heat exchanger for heat regeneration which heats the inlet air by exhaust gases. The application of such a solution rapidly increases the efficiency of the unit. The energy efficiency of modern microturbines used in small-scale CHP units is comparable with the efficiency of much larger gas turbines. Microturbines manufactured today reach about 32 per cent electrical efficiency. The performance of some commercially available CHP units with microturbines is presented in Table 4.2.

Table 4.2. Energy performances of the exemplary commercial microturbine based CHP units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Electric power, kW	65	80	100	100	350
Electric efficiency, %	28.8	25.7	30	27.6	32.1
Heat production, kW	120	150	155	172	582
CHP ratio	0.54	0.53	0.65	0.58	0.6
Overall efficiency, %	0.82	0.74	77	0.75	0.86

Combined heat and power (CHP) units based on Stirling engines

A Stirling engine is an external combustion engine operating by cyclic compression and expansion of the working fluid at different temperatures. In such an engine heat is converted into mechanical work. The heat used to drive the engine is delivered from outside to the cylinders, which are completely sealed. The engine was originally designed by the Scottish inventor Robert Stirling who received his first patent in 1816. The first Stirling engines used air as working gas, but in modern engines hydrogen and helium are also applied. A typical Stirling engine works with two cylinders: a hot (compression) cylinder, and a cold (expansion) cylinder. Such a unit is presented in Figure 4.11. The cylinders are linked together, and very often a heat regenerator is also applied between them. The heat regenerator

increases the thermal efficiency of the Stirling engine compared with a unit without such a heat exchanger.

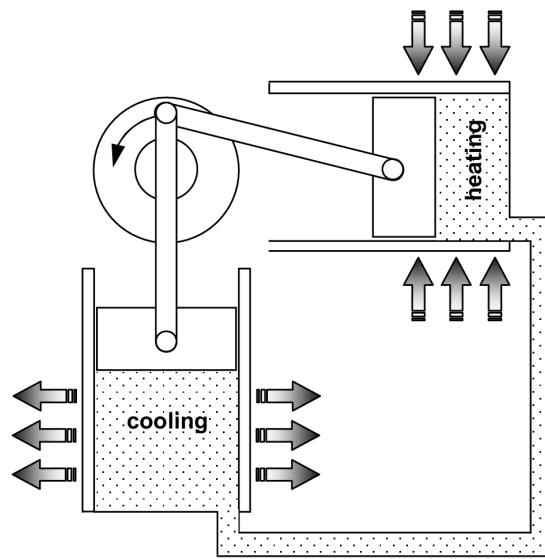


Fig. 4.11. Typical two-cylinder Stirling engine

There are many possible configurations of the Stirling engine. The engines can be distinguished by the way they move the working gas between the compression and expansion spaces. In general there are three major configurations: alpha, beta and gamma. The alpha-type Stirling engine has two pistons in separate cylinders. The heat is delivered to the hot cylinder and leaves the engine through the cold one. It is a quite efficient configuration, but there are some material problems due to the relatively high temperature of the working hot cylinder and its seals. A beta-type engine uses two power pistons working in the same cylinder on the same slider. Such a solution solves the technical problems of moving the hot cylinder and its seals. A gamma-type engine is a beta Stirling engine in which the power piston moves in a separate cylinder along the displacer piston cylinder, but it is still connected to the same flywheel. The working gas in the two cylinders can flow between them. Such a solution is mechanically simpler but generates a lower compression ratio. There are many more configurations of Stirling engines (e.g., rotary and free-piston engines), but they are not used in complex buildings.

A great advantage of the application of the Stirling engine is the possibility of using an external heat source. Theoretically Stirling engines may be driven by any heat source; for example, combustion gases, waste heat or solar energy. Stirling engines work with a rather low efficiency but the possibility of using renewable energy sources makes them a really

attractive solution for application in complex buildings. In buildings waste heat may also be used for heating, and the cogeneration technology may be realised.

Even solid fuels may be used to drive a Stirling engine. There are many examples of successful projects with units fed with wood pellets, straw, sawdust and other types of biomass. The biomass may be burnt directly in the unit or gasified and then used as gaseous fuel in the combustion chamber. Figure 4.12 shows the block diagram of a CHP unit with direct combustion of the biomass.

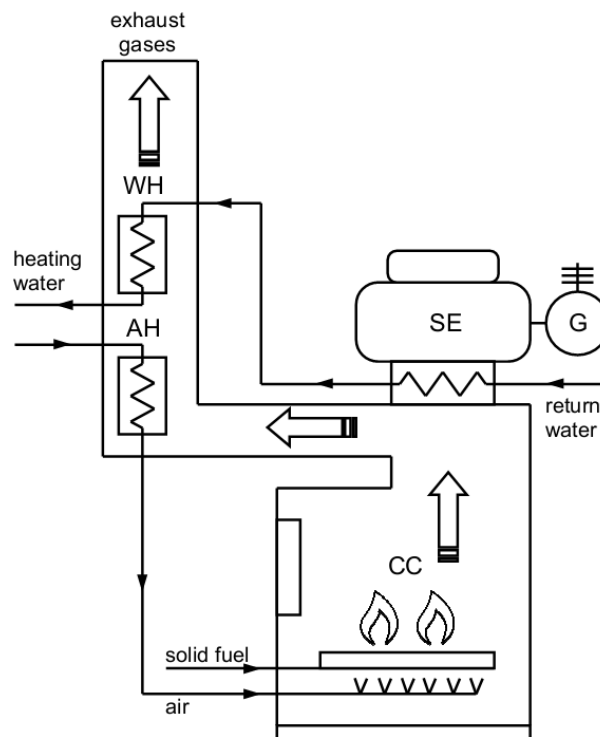


Fig. 4.12. Diagram of CHP unit based on Stirling engine powered by biomass; CC - combustion chamber, G -generator, SE - Stirling engine, AH - air heater, WH - water heater

[15]

The size of a typical Stirling engine for buildings ranges from one to 200 kW, but in some applications larger units are also used. Nowadays small natural-gas-powered CHP units are more and more popular, used not only in commercial but also in residential buildings. Table 4.3 shows the performance of exemplary CHP units with a Stirling engine powered by renewable energy sources.

Table 4.3. Energy performances of exemplary commercial CHP units with a Stirling engine

	Fuel	Working gas	Electrical power	Heat flax	Overall

					efficiency
Unit 1	Biomass	Helium	75kW _e	475 kW _t	86%
Unit 2	Biogas	Hydrogen	43kW _e	90 kW _t	75%-80%
Unit 3	Wood pellets	Helium	35kW _e	140kW _t	87%
Unit 4	Biogas	Helium	10kW _e	26 kW _t	89%

Combined heat and power (CHP) units based on fuel cells

Another possibility for cogeneration in complex buildings is the application of fuel cells. A fuel cell is an electrochemical device which directly converts the chemical energy of a fuel into electricity. The production of electricity in the fuel cell results from the reaction between the fuel and an oxidising agent [6]. The principle of operation of the fuel cell is similar to electrolysis, but vice versa; that is, gases such as hydrogen and oxygen (or air) are pumped in, and DC electricity is the output. The oxidation (combustion) consists in the flow of electrons from the external electronic orbit of the fuel atoms to the external electronic orbit of the oxygen atoms, completing them into electron octets. In a traditional combustion chamber this occurs at a high temperature. If, however, this process is divided in such a way that first on the fuel electrode the fuel atoms emit electrons and these are passed by the electrical circuit to the oxygen electrode, in the external electrical circuit electrical current will flow. In contradistinction to high-temperature combustion in the combustion chamber, the conversion of the chemical energy of fuels to electricity taking place in the fuel cell is often called “cold combustion”. Thus, this conversion takes place without combustion, and its products are electricity, heat and water. There are few or no harmful emissions. The idea of a hydrogen fuel cell is presented in Figure 4.13. This technology was developed in the nineteenth century, but the first commercial applications were introduced in the 1990s.

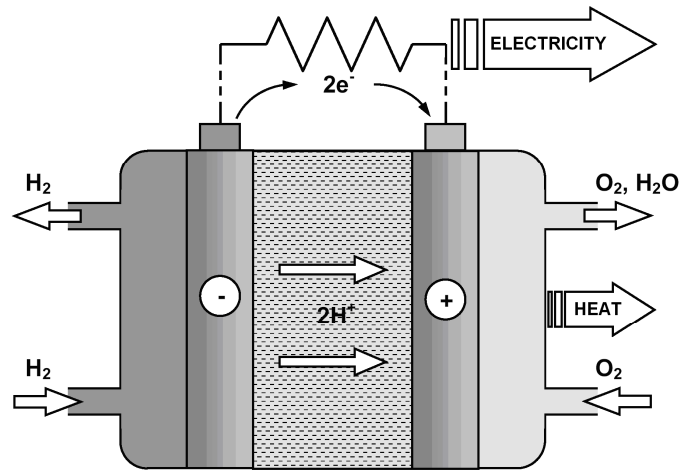


Fig. 4.13. Hydrogen fuel cell

At present there is a wide variety of fuel cell types, each using different fuels, electrodes, electrolytes and so on. Fuel cells may be classified by the type of electrolyte which is used: Alkaline Fuel Cell (ACF), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid-Oxide Fuel Cell (SOFC). A summary of the main fuel cell types and their characteristics is presented in Table 4.4.

Today fuel cells are not yet produced on a large scale, but some of their positive features may lead to their application in complex buildings in the near future. At present there are only a few fuel cell producers who offer commercial units applicable in complex buildings. Nevertheless, interest in this technology is continually rising, which is confirmed by a significant number of new demonstration projects with fuel cells in CHP units. Many of them are installed in commercial buildings.

Table 4.4. Classification of fuel cell types and their characteristics

Fuel cell type	Power range, kW	Working temperature, °C	Electrolyte	Reforming	Electrical efficiency, %	Overall efficiency (CHP), %
ACF	<100	60-100	Aqueous potassium hydroxide (KOH)	-	60-65	-
PEMFC	<250	60-120	Sulphonated organic polymer	external	35-46	60
PAFC	<1000 (most often about 200)	150-220	Phosphoric acid	external	35-44	80
MCFC	<2000 (most often about 250)	600-700	$\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$	external/internal	45-56	85
SOFC	<3000 (most often about 200)	700-1000	$\text{Y}_2\text{O}_3/\text{ZrO}_2$	external/internal	44-55	85

Heat generated during the process in the fuel cell may be successfully used in a CHP unit, just as heat from piston engines or a microturbine may be used. The advantages of CHP units with fuel cells are a small number of moving parts, silent operation without vibrations, and higher electrical efficiency (by about ten per cent) in comparison with CHP units with a traditional piston engine or a microturbine. The output load in such CHP units may be easily changed within a wide range. CHP units with fuel cells can operate continuously for a long time without breaks for repairs.

Besides the traditional application of fuel cells in cogeneration plants producing heat and electricity, the newest concepts propose the application of fuel cells in hybrid units together with gas microturbines [11]. At present such units are not available on a large commercial scale due to their complicated construction, but their high energy performance may change this in near future. The electrical efficiency of such hybrid units reaches 70 per cent in small units and nearly 75 per cent in larger ones. In most cases hybrid units use the SOFC type. This type of hybrid unit is presented in Figure 4.14.

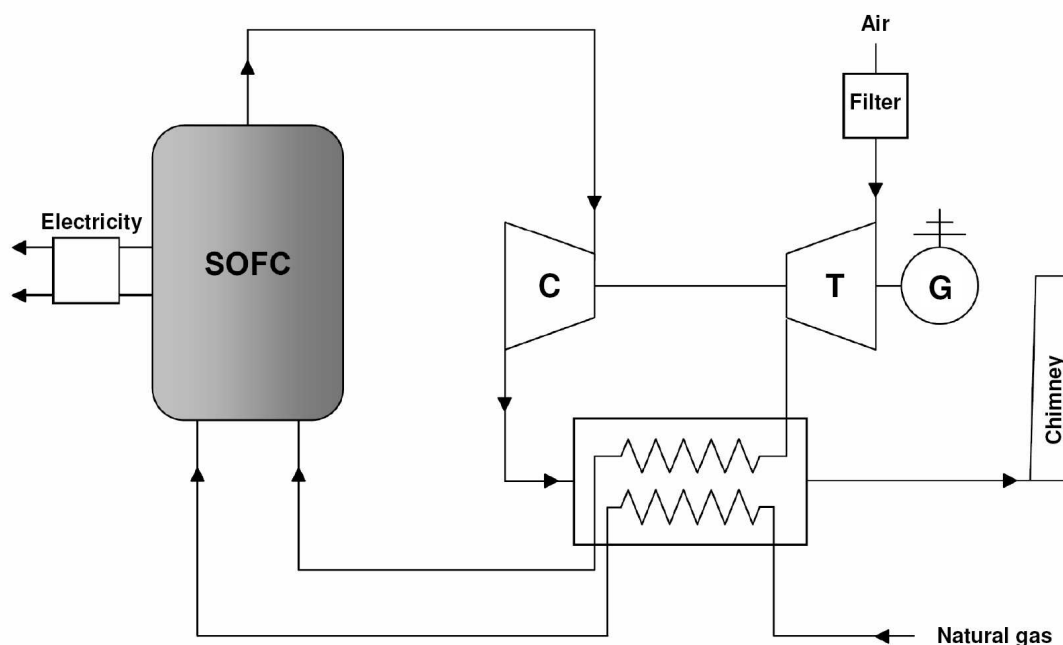


Fig. 4.14. Hybrid cycle of fuel cell and gas microturbine

Trigeneration technology for complex buildings

Modern complex buildings are characterised by a composite structure of energy management resulting from the generally growing application of various kinds of installations for heating, ventilation and air-conditioning. Many buildings require electricity, heating and cooling,

simultaneously. That provides opportunities to use waste heat for cooling and the application of trigeneration systems [9, 10]. The term “trigeneration” means an integrated CHP unit with a cooling aggregate. This integration allows generation of heat, electricity and a cooling agent in one system. As a heat source the heat from a piston engine, microturbine or, for example, a fuel cell can be used. Especially in out-of-heating seasons those sources dispose large amounts of waste heat. Waste heat may be successfully used for the production of cooling agents, which is necessary for air-conditioning or other cooling systems (e.g., food storage and air dehumidification). The application of trigeneration systems in buildings is called building, cooling, heating and power (BCHP) technology. Such solutions in buildings utilise input energy in a very efficient way and are becoming more and more interesting [14].

One of the most efficient ways to utilise waste heat for cooling is to apply absorption cooling devices. Absorption chillers, in contradistinction to compressor refrigerators, do not require much mechanical energy. These devices are characterised by high durability, high reliability, low vibration and low noise emission. Therefore absorption chillers are nowadays the most popular units for BCHP applications.

Usually absorption chillers in BCHP systems are powered with hot water or steam, or directly with hot exhaust gases. At present, the two most popular types of absorption chillers on the market are lithium-bromide and ammonia chillers. In most cases for BCHP systems in buildings (cooling, air-conditioning and so on) lithium-bromide machines are used. The absorbent in this kind of device is environmentally friendly lithium-bromide ($\text{LiBr}+\text{H}_2\text{O}$), and the working fluid is water. In buildings where a lower temperature is required ammonia absorption chillers are applied. In such machines the ammonia solution ($\text{H}_2\text{O}+\text{NH}_3$) is used as a working fluid. It allows to decrease the temperature of the cooling agent to below 0°C . Such devices, in comparison with lithium-bromide chillers, are more complicated and more expensive.

Due to the toxicity of ammonia they require special construction solutions and extra technical maintenance to ensure operational safety. In presently offered single-stage absorption chillers the coefficient of performance (COP) reaches a level of 0.8. In the case of double-stage machines this coefficient is much higher and reaches a value of 1.5. Triple-stage chillers do not yet reach a satisfactory technical level, and they are not commercially used on a wide scale in complex buildings. Basic energy characteristics of single- and double-stage absorption chillers have been gathered in Table 4.5.

Table 4.5. Energy parameters of single- and double-stage commercially available absorption chillers

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Cycle type	1-stage	1-stage	1-stage	2-stages	2-stages
Heat source	hot water 90-130°C steam	hot water 95°C	hot water 90-130°C steam	hot water 180°C steam	hot water 180°C steam
Cooling power, kW	394	1055	2008	1266	2318
Coefficient of performance COP	0.63	0.7	0.71	1.20	1.21
Electricity consumption, kW	3.8	4.05	9.7	10.6	20.5

A block diagram of the typical B CHP system for heat, power and cooling production is presented in Figure 4.15. In this system a piston engine and absorption chiller have been applied. Additionally, in order to cover the peak heating demand a peak boiler and storage tank have been used. When the heat consumption is lower than its production in the B CHP unit, the heat accumulates in the storage tank of hot water. When the demand for heat is larger, the heat storage tank provides heat to consumers. In periods of increased heat demand the peak boiler connected with the B CHP unit is switched on and produces additional heat.

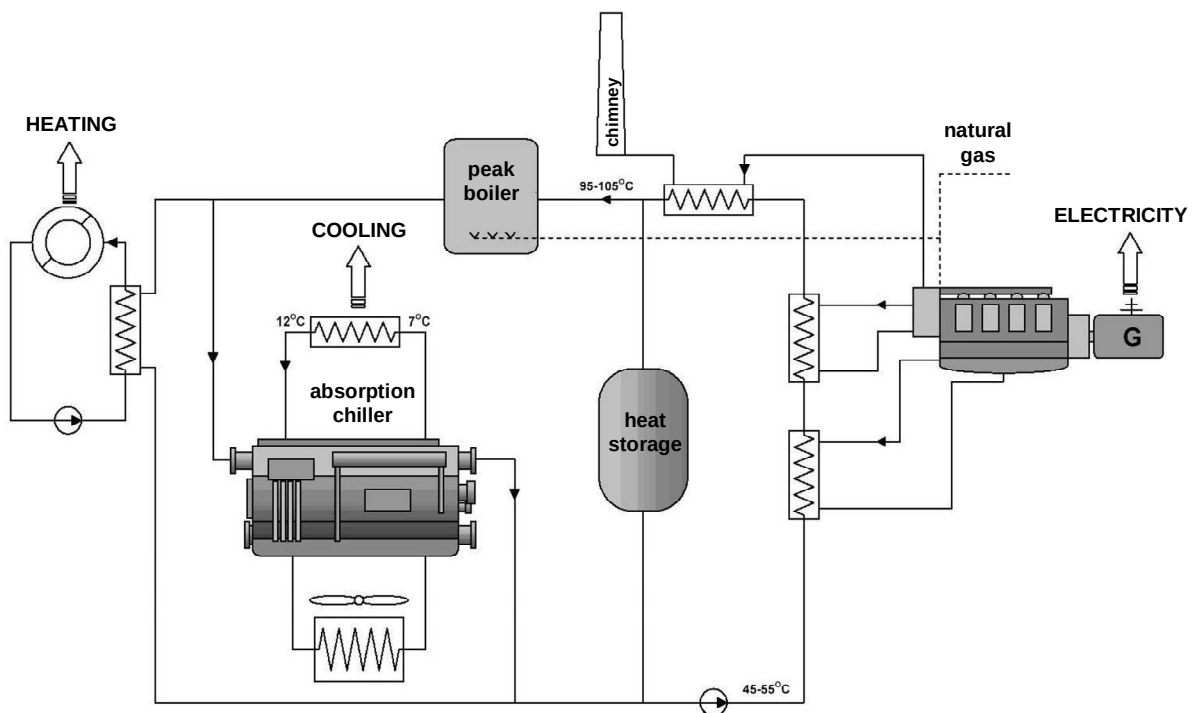


Fig. 4.15. Block diagram of the typical BHP system with application of the absorption chiller

It is also possible to integrate both absorption and compressor chillers in the BCHP system. Such a solution is presented in Figure 4.16.

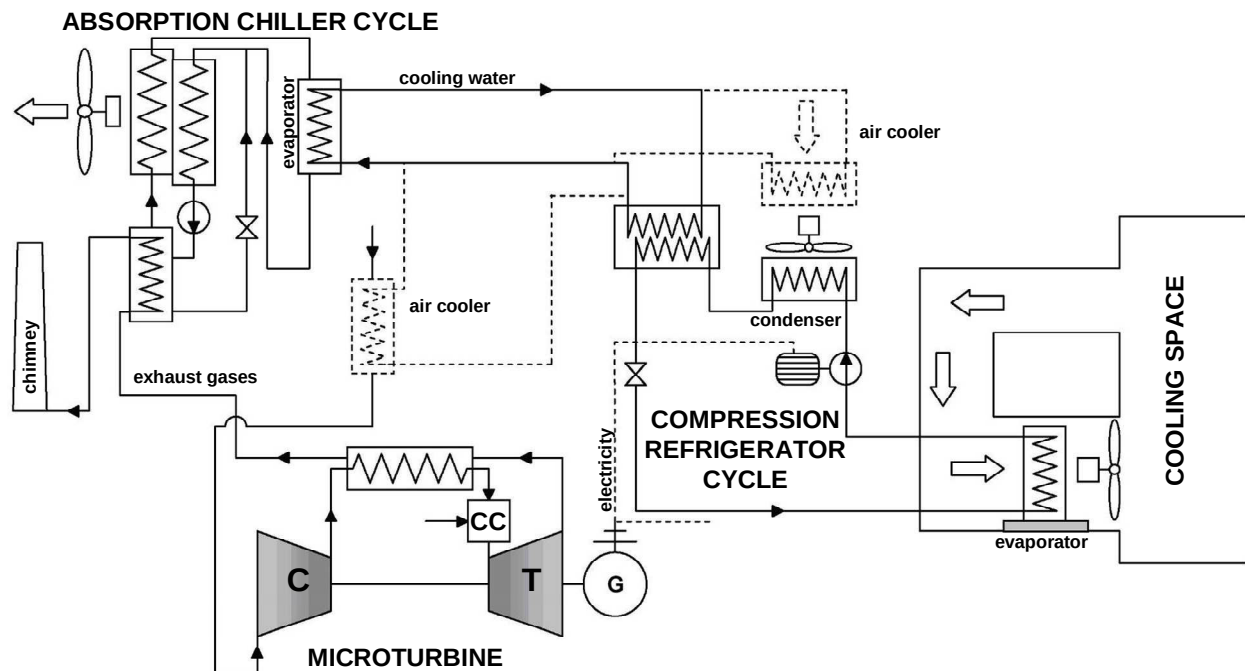


Fig. 4.16. Block diagram of the BCHP system integrated with both absorption and compressor chillers applied in complex buildings [13]

4.3. Utilisation of renewable energy resources in complex buildings

Renewable energy is defined as energy which comes from the natural environment and is constantly or repetitively replenished. Nowadays, there are many possibilities for generating energy by applying renewable energy resources. Most renewable energy systems (plants) are set up for the production of some particular energy carriers and their sale to the distribution network (e.g., electricity from a hydro-power plant). Therefore, there is also a large potential for renewable energy to be used in the vicinity of complex buildings.

4.3.1. Solar energy

Active solar heating - solar collectors

One of the most efficient ways to utilise solar energy in buildings is to apply solar collectors for space heating and the production of hot tap water. Such a process may be realised by

many different types of solar collectors. Solar collectors have often been applied in single house-heating systems, but nowadays they are also more and more popular in complex buildings. They may be mounted vertically on the wall of the building or on its roof. Figure 4.17 presents roof-placed solar collectors.

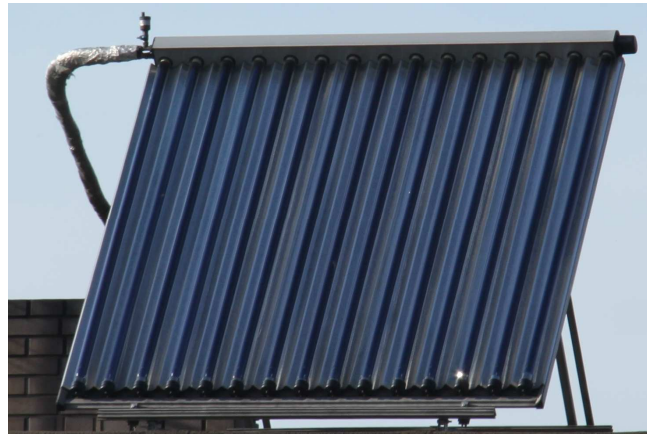


Fig. 4.17. Roof-placed solar collector

Flat-plate water solar collectors. These collectors consist of an absorber plate, a glazing cover (sometimes a plastic cover), casing and insulation (Fig. 4.18). The absorber plate should be painted black to absorb most of the solar radiation. A good quality glazing is very important. In most cases there is only one layer of glass, but more efficient solar collectors sometimes have two glazing layers. Due to the internal greenhouse effect only a small amount of the heat captured by the absorber escapes the solar collector.

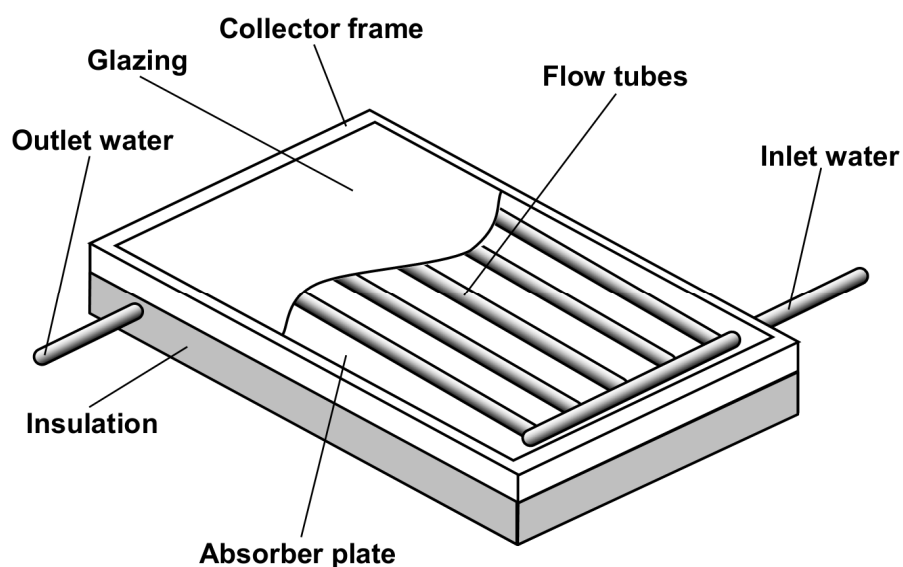


Fig. 4.18. Flat-plate water solar collector

Evacuated tube collectors. Collectors of this type are made up of rows of parallel tubes in which the working fluid circulates. There are several kinds of evacuated tube collectors. The most effective solution is heat pipes with special low-vaporising fluid. The pressure value of the fluid is chosen to guarantee evaporation at the hot part and condensation at the cold part. Such a solution provides a very efficient heat transfer, but is relatively expensive. The concept of evacuated tube collectors is presented in Figure 4.19.

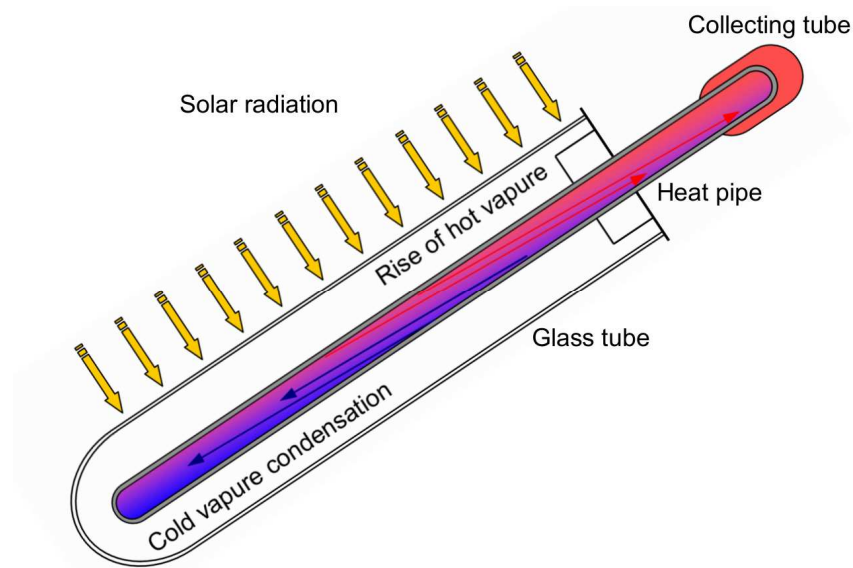


Fig. 4.19. Evacuated tube collectors with heat pipe technology

Flat-plate air solar collectors. In these collectors (Fig. 4.20) air is used instead of water as a working fluid. Air collectors are generally less efficient than water collectors, but their construction is simpler and less expensive. They are often applied for space air heating and drying systems.

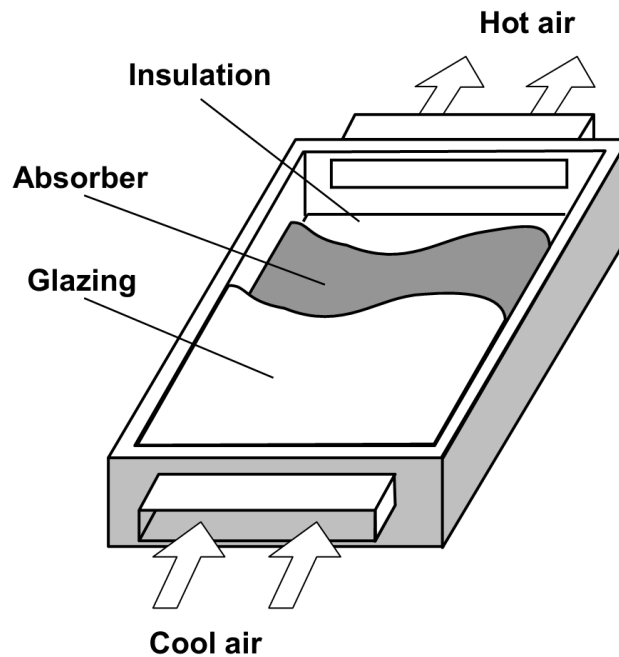


Fig. 4.20. Flat-plate air solar collectors

Unglazed solar collectors. These are not as efficient as glazed collectors but are a cheaper solution often applied in water heating systems of swimming pools. The temperature of water in swimming pools is relatively low in comparison to a space heating system or the preparation of hot tap water, so that the efficiency of these collectors is less important.

Solar concentrators. These systems use mirrored surfaces concentrating solar radiation. They are not commonly applied in building heating systems. They are used rather as a heat source to drive heat engines for electricity production. Some demonstration applications with a steam turbine and with Stirling engines exist. The advantage of these systems is the possibility to heat the working fluid to a high temperature. Such systems are quite expensive because there are only a few manufacturers in the world producing solar concentrators. The best effects are achieved when the mirrors track the sun using a special mechanical system which rotates the concentrators in two axes (both horizontally and vertically). As distinct from flat-plate collectors, the solar concentrators can only focus direct sunlight, and therefore they do not act well in cloudy weather. There are two types of concentrators: line-focus and point-focus ones.

Solar radiation varies during the day, strongly depending on weather conditions. The heating demand also changes at the same time. Accordingly, the application of thermal storages for such systems may be very useful. In most cases thermal storage is realised using tanks with

hot water, but there are also solutions with ground thermal storage systems. In huge heating systems it is possible to realise inter-seasonal thermal storage, but this requires large well-isolated storage tanks, and in most cases such solutions are not useful.

Passive solar heating and day lighting

Besides directly using solar energy in solar collectors, buildings with appropriate design may also use passive solar techniques. Such techniques may be used to increase significantly the performance of heating, cooling, lighting, ventilation and dehumidification systems. In some cases passive solutions may completely displace conventional systems. There are some basic features which should allow a building to use passive solar heating in the best way:

- a large area of glazing surfaces to gain heat from solar radiation,
- well-controlled and efficient heating systems with a load which is adjustable to the quantity of passive solar heat gains in the building,
- orientation of the building rather southwards to capture as much solar radiation as possible,
- massive partitions in the building, which absorb sun radiation during the day and heat the internal air during the night very well; a massive construction of the building prevents overheating in summer,
- good insulation to reduce heat losses,
- location of the building away from shading by other buildings and trees.

Electricity consumption for lighting in complex buildings is significant. For example, in most office buildings the lighting is continuously switched on during all working hours (even in sunny weather) and consumes about 30 per cent of the electricity delivered to the building. By applying appropriate design solutions in buildings it is possible to achieve high energy savings for lighting. Of crucial importance is that the design solutions should consider both daytime lighting and passive heating simultaneously. Good daytime lighting conditions lead to high heat gains, which may be very inconvenient during the summer season. Typical daytime lighting techniques are:

- roof windows and glazed roofs,
- appropriate design so that most rooms are penetrated by daylight,
- light wells inside the building,

- tall glazing on the facade of the building which allows the interior of the building to be lit up.

Solar photovoltaics

Photovoltaic (PV) cells produce electricity directly from solar radiation without any mechanical devices. The PV panels (Fig. 4.21) are silent, easy to handle and easy to arrange in a building. PV systems may be mounted on roofs and walls of complex buildings, partially substituting some traditional covering materials. Complex buildings are occupied in most cases during the day when the solar radiation may be used for electricity production, so there is no special need for energy storage. The best solution for complex buildings is PV systems working in the on-grid mode, where the surplus of electricity is sold to the national power system.

The overall effectiveness of the PV system in complex buildings depends on:

- geographical location of the building and local meteorological conditions,
- location of the PV panels on the building (azimuth and elevation) and application of the sun tracking system,
- area of the PV panels,
- energy efficiency of the PV panels,
- energy efficiency of auxiliary electrical devices (e.g., efficiency of the DC/AC inverter).



Fig. 4.21. PV panels located on the roof of an office building

A very interesting solution is the combination of PV panels with shading devices, so-called “shadovoltaic” or “photovoltaic solar shades”. In this case the solar shading elements (movable or fixed) are covered by PV panels. Accordingly, such systems may efficiently reduce the solar heat gains and produce additionally electricity.

4.3.2. Wind energy

Complex buildings, especially office buildings, are often very high structures. This feature permits the use of wind energy. Electricity may be generated in small wind turbines (micro-turbines). Such devices are commercially available, and there are two main kinds: with a vertical axis, and with a horizontal one. These compact turbines are often mounted on the top of a building, but there are some disadvantages of such a solution. During their operation micro wind turbines vibrate, and the vibrations are transmitted to the building structure, which may be perceptible by the occupants as an unpleasant noise. Moreover, in nearby buildings turbulences are generated which deteriorate the working conditions of the wind turbines. Tall towers for rotors of the wind turbines allow this problem to be partially minimised, but such constructions are quite massive (for safety reasons) and expensive. Figures. 4.22 show examples of rooftop wind turbine supplying energy to building.



Fig. 4.22. Micro wind turbines (www.preVent-germany.com)

4.3.3. Ground source heat pumps for complex buildings

Heat pumps are devices which transfer heat from one space with a lower temperature to another space with a higher one. Of course, this process is possible thanks to input energy. In the case of compressive heat pumps mechanical work is applied. In buildings heat pumps may be used both for heating and cooling. The low temperature heat source is in most cases the ground, from which the heat is transferred using vertical (Fig. 4.23) or horizontal heat exchangers. The heat is delivered to the exchanger of the heating system. The application of heat pumps may significantly increase the effectiveness of cooling systems with absorption chillers. There are also internal applications of heat pumps for appropriate heat management in buildings. In such systems waste heat from cooling zones in a building is used for heating in other zones. Such a solution increases the efficiency of cooling and heating systems and leads to significant energy savings in a building. In general, from the operational point of view, the heat pumps in complex buildings may be divided into the following categories:

- heat pumps working only in the heating mode, providing space heating and/or water heating,
- reversible heat pumps working in the heating and cooling mode, providing both space heating and cooling (air-to-air heat pumps or with a water loop),
- heat pump systems integrated with exhaust-air heat recovery,
- heat pumps with water heaters, fully dedicated to water heating.

In complex buildings the peak load is covered by a traditional heating system, using a peak water boiler powered by heating oil or natural gas. Of course, heat pumps can be integrated with other heating or cooling systems. For example, the heat pump may work in one system with a cogeneration or trigeneration unit in the building.

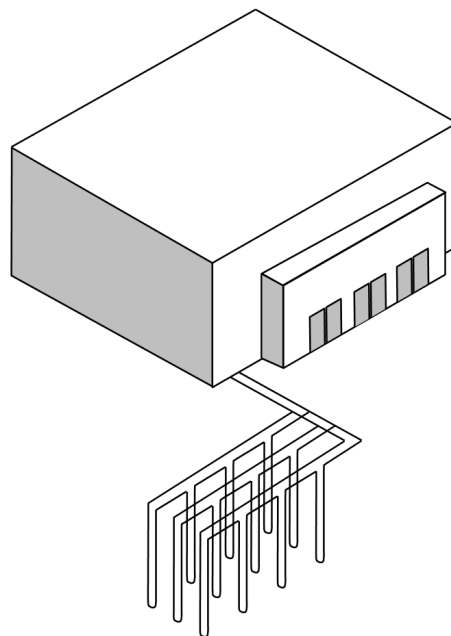


Fig. 4.23. Ground heat pump for a commercial building with a vertical heat exchanger

4.3.4. Bio-energy for complex buildings

Bio-energy is a kind of renewable energy contained in substances supplied from the natural biological environment, which may be used directly in energy devices (e.g., boilers). It is called biomass. From biomass it is possible to produce many kinds of biofuels (e.g., biogas). The chemical energy accumulated in biomass arises mainly thanks to solar radiation. This is why bio-energy may be considered to be solar energy accumulated in organic substances.

Direct biomass combustion and biomass gasification

There are many kinds of biomass which may be utilised in complex buildings, the most popular ones being:

- raw wood, derived from the processing of wood or forestry activities (e.g., sawdust, wood chips and wood pellets),
- energy crops (e.g., willow and poplar),
- wastes from agricultural cultivations (e.g. straw),
- wastes from the food industry and consumer food wastes,
- by-products from the wood industry.

Biomass is mainly used for heat production in complex buildings, but there are some innovative projects for electricity generation, too. A serious problem in buildings is the lack of place for storing the biomass and the wastes from combustion processes. Complex buildings are often located in urban areas. Therefore the transport of the biomass is also difficult. Direct biomass combustion in such places may turn out to be difficult or even impossible due to emissions to the atmosphere. An example of a better technology for building application is biomass gasification. This process transforms the biomass into fuel where synthesis gas is produced, which is much cleaner than direct combustion in the boiler. Biomass gasification increases the possibilities of applying cogeneration plants in complex buildings. Such units (CHPs based on piston engines, Stirling engines or even microturbines) very efficiently utilise the chemical energy of the biomass and emit less noxious substances to the environment. Some demonstration projects exist that apply direct biomass combustion in cogeneration or trigeneration technology in complex buildings. For this purpose Stirling-engine-based CHP units are most promising. Similarly, some demonstration installations of direct biomass combustion in buildings use Organic Rankine Cycles.

Biofuels

Biofuels are fuels gained by the conversion of biomass and bio-wastes. Nowadays there are many kinds of biofuels, which depend on the bio-materials from which they are derived and the type of production process in which they are used. There are some possibilities for utilising biofuels in complex buildings, where the biofuels may feed the heating boilers as well as the cogeneration and trigeneration plants. Such devices must be specially adapted for biofuel combustion (in most cases producing less chemical energy and higher emissions if compared with conventional fuels) or even designed for such fuels. A simpler way to use

biofuels is in a co-firing process with conventional fuels. In complex buildings the following biofuels may be used:

- bioalcohols,
- biodiesel,
- green diesel,
- vegetable oil,
- bioethers,
- biogas,
- syngas.

The potential to utilise biofuels in complex buildings is rather limited. The main problems encountered are:

- complex buildings are often located in urban areas; some biofuels (e.g. biogas) are produced in very complex installations, which should not be located near those buildings,
- transport of biofuels in urban areas is quite complicated.

Besides gas and liquid biofuels, solid ones are also produced. However, the limited availability of such fuels and difficulties connected with their combustion in complex buildings restrict the application of these biofuels.

4.4. Supply of energy carriers to complex buildings

4.4.1. District heating supply systems

In the case of district heating, heat is supplied to a complex building by a heating medium via a heat exchanger centre, which transfers the heat from the internal heating network to the heating installation of the building. The heating medium is a substance transporting the heat from the CHP or heating plant to the receiver through the heat distribution network. In the building both liquid and gas heating media may be applied. Each heating medium should comply with the following requirements:

- high thermal capacity,
- low flow resistance,
- low cost,

- low toxicity,
- boiling point parameters.

Owing to these requirements the most popular heating media are water, steam and air.

Water is an easily available heating medium, but in most cases it is contaminated by some organic and chemical substances. This is why, before its use in the heating network the water should be conditioned in a water treatment system. An inconvenience connected with the application of water as a heating medium is its boiling and freezing temperatures. In order to prevent boiling a suitable pressure in the heating network should be kept up. In winter the water heating network should be protected against freezing. Because of chemical contaminations the other main problematic features of the water heating medium are the following ones: the possibility of gas precipitation from water (air lock of the heating network), boiler scale formation inside the heating installations, and pH reaction responsible for corrosion of the installations. There are also special liquid heating media (e.g., mineral oils and glycol), but their application in heating systems of complex buildings is rather limited.

In some heating networks (especially in industrial systems) steam is used as a heating medium. Such systems have a similar structure as water systems, but due to the properties of steam they are more complicated to maintain. They also work in closed loop cycles like water systems. In the heat exchanger of the consumer the steam condenses to water. The water condensate is collected and pumped to the heating source (CHP or heating plant).

The main problems in the maintenance of steam systems are:

- limited possibilities for heat transport at long distances,
- relatively high temperature of the steam compared with water,
- necessity of removing the condensate from the pipes.

Steam heating systems are not commonly used in complex buildings. Sometimes such applications occur in buildings in the neighbourhood of industrial plants, where heating steam is available.

In special locations air may be applied as a heating medium in a building. For example, the heating air may be delivered to the building from nearby industrial installations. Due to a low heat capacity, a high density with the rise in temperature, and the possible formation of fog, the use of air as a heating medium is expedient only to connect the functions of heating and ventilation in the building.

4.4.2. Electricity supply

Complex buildings are connected to the high voltage power network and use transformers to reduce the voltage to the appropriate value for the equipment inside the buildings. These transformers and other electrical equipment may be placed inside or outside buildings, usually near the main power network terminal. They are the most important electrical devices in the whole power system of buildings.

In complex buildings several different types of transformer constructions are used:

- *Ventilated dry-type transformers.* The generated heat is removed by the ventilation air. Such units need enough space to ensure an appropriate air circulation. This type of transformer should be located inside a restricted area for safety reasons and to prevent mechanical damages. Such a transformer is very popular in complex building applications.
- *Sealed dry-type transformers.* The construction of these transformers is very similar to that of dry-type transformers, but they have an additional tank with dielectric gas (e.g. nitrogen) to protect the windings. Such transformers can be installed outside or inside the building. They are often applied in toxic or corrosive environments. They are very reliable devices and require minimum maintenance.
- *Cast-coil transformers.* These consist of windings encapsulated in reinforced resin. Such solutions protect the windings against contaminants and moisture.
- *Unventilated dry-type transformers.* The construction of these transformers is similar to that of ventilated transformers, but all electrical parts are enclosed. The tight case permits such transformers to be applied in unfriendly conditions (contaminated, wet or toxic).
- *Oil-filled transformers.* The windings of these transformers are closed in a tank filled with insulating oil. The oil helps to control the temperature inside the transformer and prevents overheating during high power applications. Such transformers can operate for long periods of time and are very safe.

4.4.3. Water supply

Water supply systems get water mainly from groundwater sources and surface water locations (e.g., rivers) and supply it to buildings. The water is then, in most cases, purified, disinfected by chlorination and sometimes fluoridated. Then the treated water either flows by gravity or is pumped to reservoirs. After that it is delivered to consumers. Once the water is used,

wastewater is typically discharged to a sewer system and treated in a wastewater treatment plant before being discharged into a river, lake or the sea, as well as for irrigation or industrial use. Typical water supply system consists of the following elements:

- Raw water source located below or above the ground, as underground aquifer, a river or a lake. The raw water is transported to the water treatment system.
- Water treatment system. The raw water is prepared for drinking purposes.
- Drinking water reservoirs with necessary facilities (e.g. water pressure towers, pumping stations, etc.).
- Drinking water distribution network system which delivers the water to the consumers.

Drinking water contains micro-biological and physico-chemical contamination. There are many parameters of water quality. In public water supply systems water should at least be disinfected – most commonly by chlorination or the use of ultra-violet light, or it may need some other additional treatment, especially in the case of surface water.

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CHAPTER 5

Supply of heat, cogeneration and trigeneration

Complex buildings belong to the municipal sector of the domestic economy, whose share in the demand for final energy carriers is considerable. The demand for final energy carriers (electricity and heat) can be covered by centralised supplies or distributed energy systems and also both of them jointly.

The heat demand for heating purposes, ventilation and air-conditioning depends on the external temperature presented in the form of a duration curve characteristic of the given climatic zone. Thanks to the application of hot tap water tanks the demand for heat for the production of hot tap water is stable although the 24-hours diagram of the consumption of hot tap water is characterised by considerable fluctuations.

In district heating networks that supply complex buildings qualitative, quantitative or both of these methods of control are applied. In the complex buildings themselves the consumption of heat can be also controlled locally (e.g., pulsatory control by changing the time of operation).

The application of heat pumps in complex buildings depends on local conditions (availability of an adequate bottom source of heat and the efficiency of providing driving energy). Both in the case of the system of centralized supply of heat and distributed energy systems, the application of cogeneration of heat and electricity is more effective due to energy and economic reasons than the separate production of heat and electricity. If district heating systems are situated near system power stations, high efficiency in the production of heat is displayed by the power unit adapted for heat production. Gas, as well as gas-and-steam CHP plants are not only ecologically more favourable, but particularly in the case of a combined cycle gas turbine also energetically more effective than CHP plants powered with coal. Small-scale CHP plants fired with gas are generally applied in distributed energy systems. The joint application of a CHP plant and the production of cooling agents leads to “trigeneration” technology. The application of an absorption cooler improves the mean annual efficiency of a CHP plant thanks to the partial equalisation of the heat loads (increased production of heat in the off-heating season).

Directive 2004/8/EC on the promotion of cogeneration applies the index *PES* (Primary Energy Savings) as a measure of energy effectivity of cogeneration. In small-scale and micro-cogeneration units $PES > 0$, and in the case of cogeneration units with a power rating equal to 1 MW_e and more the index *PES* amount to at least to 10 per cent, which qualifies these

units as high-efficiency cogeneration and entitles them to obtain guarantees of origin concerning electricity production. A comparison of *PES* concerning various technologies of cogeneration indicates the high effectiveness of gas, as well as gas-and-steam cogeneration units.

5.1. The municipal energy sector as a part of the energy system of the country

Complex buildings constitute some part of the municipal sector of the national economy. The share of this sector in the consumption of final energy is considerable, often amounting to about 40 per cent. Final energy is used for heating, the production of hot tap water, cooling, lighting, catering and supply of electricity to electrical devices.

The municipal demands for heat are covered by:

- large-scale CHP plants,
- large-scale heating plants,
- local boiler houses,
- small-scale CHP's units,
- stoves.

The energy carriers for heating purposes are:

- hard coal,
- domestic coke,
- wood,
- natural gas,
- fuel oil,
- electricity.

The share of the respective kinds of fuels and electricity varies from country to country. Direct consumption of electricity for heating purposes is rather less applied. The group of heating installations that use electricity also includes heat pumps. The application of heat pumps is connected with a reduction of the temperature in internal heating networks not exceeding 45°C. This is the same in the production of hot tap water and heating the water in swimming pools.

In the climatic conditions of northern and central Europe the application of solar energy for the purposes of heating and production of hot tap water is rather limited. Usually additional heating systems must be used. For this purpose heat pumps (if they are profitable)

or heating boilers are used. Some part of the heat demand for heating purposes may be covered by geothermal water.

The demand for energy required to keep up an adequate thermal comfort in buildings can be reduced, first of all, by applying partitions with more efficient insulation, including windows and doors. A rational architectural solution of the building structures is of great importance. In some situations buildings have an outer surface nearly 40 per cent larger than in the case of energy-saving solutions. Sometimes architects design extremely large glassed surfaces, which increases heat losses.

In some countries the difference between the consumption of hot tap water in households supplied from thermal centres (without water meters in the flats or houses) and the consumption of water in households provided with gas or electric heaters is considerable. In households with water meters the consumption of hot tap water is assumed to be half that of in households supplied centrally (without water meters).

Internal installations should be applied in such a configuration that heat meters can be installed and programmed temperature control may be applied, along with microprocessors. Automation and control applied comprehensively in thermal centres connected with heating networks permit considerable savings in energy required for heating rooms. An essential condition of a rational consumption of heat is the introduction of separate heat meters for room heating and hot tap water. It is possible to apply electrical heating, accumulating hot water in stores which are loaded during the night when the price of electricity is lower. Such a system with microprocessing control permits to keep up a high thermal comfort in rooms over 24 hours, provided that the building is adequately insulated. Heating by means of electricity is comfortable because it is easily handled, without causing noise and vibrations and a direct contamination of the environment. Usually however, it is characterised by considerable thermodynamic imperfection because, besides large exergy losses during the heat transfer from the heater to the heated room, there are also high losses of exergy caused previously in the course of production (in thermal power plants) and transmission of electricity, increasing its costs. Therefore, usually, accumulative electrical heating is used, as has already been mentioned.

Solar collectors are most suitable for the production of hot tap water because they can be exploited all the year round. For heating purposes their application is less effective, because during the heating season their efficiency is lower than in summer. This concerns northern countries. The energy efficiency of a solar collector depends to a large extent on its construction. While choosing its structural parameters, its efficiency ought to be taken into

account, as well as the duration curve of the intensity of solar radiation together with the duration curve of the demand for heat.

5.2. Ways to meet the demand for energy carriers in complex buildings

The demand for final energy carriers (electricity, heat and cooling agents) can be covered in the following ways:

- centralised supplies from electro-energy systems and district heating systems,
- distributed energy systems,
- applying both of these ways (hybrid systems).

The centralised supply of electricity is usually based on national or regional electro-energy systems. Depending on the given country either thermal power stations fired with hard coal or lignite (e.g., in Poland), nuclear power stations (e.g., in France) or hydropower stations (e.g., in Norway) dominate. Most often, however, the electro-energy system is in the case of primary energy characterised by the so-called “energy mix” (e.g., Germany, Denmark, Sweden). These latter countries are characterised by the highest share of cogeneration in the production of electricity (e.g., in Denmark about 60 per cent). In some countries the share of wind power is considerable.

The centralised supply of heat is mainly covered by CHP plants in developed countries. CHP plants are mostly fired with natural gas or hard coal. In the case of gaseous fuels the thermodynamically most effective way of producing electricity and heat is the application of gas-and-steam cycles. Cogeneration of heat and electricity may also be realised by adapting the power station for the production of heat. This method of heat production has proven to be more effective than traditional CHP units fired with the same kind of fuels (e.g., hard coal). This may, however, be profitable if the distance from the power station to the consumers is reasonable.

Complex buildings are concentrated consumers of heat similarly as municipal consumers are, and are usually supplied from the same district heating systems. In many cases, however, complex buildings are situated too far away for the transmission of heat to be profitable. They may be treated as so-called “energy islands” in which the demand for final energy carriers is covered by distributed energy systems. Distributed cogeneration systems are often integrated with the production of cooling agents. In this way the so-called “trigeneration” systems are realised.

The construction of small-scale CHP plants in the neighborhood of the consumers permits a considerable reduction in both the cost of heating networks and losses of the

transported heat. Small-scale CHP plants are constructed, for example, in hospitals, schools, hotels, public buildings, supermarkets and so on - in short, in complex buildings. They are equipped with piston engines or small gas turbines. Piston engines may be fed with fuel oil or natural gas, as well as biogas.

Exergy losses in the course of transferring heat to heated rooms may be reduced by applying a low-exergy internal installation (floor heating, wall heating or low-temperature heaters). The application of these installations is, however, only feasible when it simultaneously leads to a reduction of exergy losses in the production of heat, which may be achieved by means of cogeneration. . The application of low-temperature internal installations permits a reduction in the mean temperature of the network water and to increase the production of electricity. A low-temperature heating system permits a reduction in exergy losses in the energy systems because these losses are much lower in a steam boiler than in a water heater [15].

5.3. Supply of heat

5.3.1. Introduction

Heat is one of the oldest forms of transforming energy applied usefully by humans. Originally it was obtained by burning wood, and later by combusting coal and other fuels. This form of utilising the chemical energy of fuels is still applied in our time. Charcoal as a form of smokeless fuel was used already by the Romans, who also invented the first central heating. It was a kind of floor heating in which the flue gases from the furnace situated underground flowed through a system of channels under the ground floor. The water containers above the furnace chamber were the first installations that provided centrally hot tap water.

In the Middle Ages air heating was applied and furnaces made of stone were used for this purpose. By burning wood the layers of stone were heated up, transferring the accumulated heat to the air inside the room. This heating system was applied, among others, in the castle of the Teutonic Knights at Malbork (Poland). In 1884, a system in which air was heated through masonry walls (with separate channels for the flue gases and the air) was applied.

About the year 1750, steam heating was invented in England (0.1÷0.2MPa) and towards the end of the nineteenth century in the United States a cast iron boiler and cast iron radiators were introduced. During the first half of the eighteenth century both in England and

in France for the first time a heating system was applied with gravitational warm water cycling. Heating with hot water under high pressure was first used in England at the beginning of the eighteenth century, mostly in industry. At the beginning of the twentieth century central heating developed quickly thanks to the application of pumps (pump heating) [5].

The first municipal heating plant was commissioned in 1877 at Lockport in the United States [5]. In 1887 in the complex buildings of the Technical University of Berlin remote control heating was applied. This system was also applied for the first time in Poland at the beginning of twentieth century, in the buildings of the Technical University of Warsaw [5]. In the year 1900, in Dresden, an extensive heat distribution network was constructed. The first district heating system fed by CHP was commissioned in 1925 in Berlin.

Heating systems may be classified as follows [5]:

- with respect to the situation of the source of heat—local, central and remote central heating,
- with respect to the kind of input energy—fired with coal, gas, fuel oil, municipal wastes, as well as electrical, solar, geothermal heating and also heating applying heat pumps,
- with respect to the kind of heat carriers—heating by means of warm water, hot water, steam and hot air,
- with respect to transferring the heat—convection, radiation, ventilation and combined heating.

For local heating the furnace is placed in the room to be heated, and in central heating a single installation (boiler) meets the requirements of all rooms in the whole building. In the case of remote central heating, a heating plant or CHP supplies complex buildings, a district or a whole town with heat. A CHP realises the cogeneration process of heat and electricity production. There are also special heating systems in which heat pumps, solar energy, geothermal energy and biogas are utilised. Besides these, so-called territorial systems of industrial waste energy recovery are also applied, in which the recovery installations (waste-heat water boilers, and installations of evaporative cooling) cooperate with the district heating systems [11]. In many towns municipal wastes are utilised, combusted in special boilers installed in the heating plants and CHP plants. Due to the low LHV ($3,3 \div 5$ MJ/kg) and its widely changing range, the combustion of rubbish is rather difficult.

5.3.2. Consumers of heat. Heat carriers.

Generally, the consumers of heat are classified as follows:

- municipal consumers,
- complex buildings,
- industry.

Municipal consumers use heat for the purposes of heating, ventilation, air-conditioning, heating up hot tap water and cooling. The demand for heat for the purposes of heating, ventilation and air-conditioning varies depending on atmospheric conditions. The principal quantity conditioning the demand for heat for these purposes is the ambient temperature presented in the form of duration curve used to calculate the demand for heat. The duration curves are set up for the respective climatic zones of the country (e.g., Poland has been divided into five climatic zones). The demand for heat required for heating is established based on calculations of the heat losses according to standards concerning various kinds of rooms and various climatic zones. For the purposes of air conditioning and ventilation the demand for heat is determined according to the required multiplication factor of the exchange of air in the room.

Complex buildings are concentrated consumers of heat, similar in their character to individual municipal consumers. They are often provided with heat by the same district heating networks. Frequently, however, they are situated at a distance which makes it unprofitable to supply them from remote central heating systems, and they are therefore called an “energy islands” in which the demand for energy carriers (including heat) is covered by installations of decentralised energy systems. Heat supplied to complex buildings from district heating networks or their own installations (heating boilers or mini-CHP units) covers the requirements of heating, ventilation, air conditioning and production of hot tap water and cooling agents. The character of the heating load depends on the function of the given complex buildings, but to a large extent it is similar to that of individual municipal consumers.

Industrial consumers require heat mainly for technological purposes, its character depending on the specifics of the given technological process. The consumption of heat for ventilation in industrial plants usually exceeds the demand for heat required for heating.

As heat carriers hot water and steam are usually used. If heat is needed only for the purposes of heating, ventilation and the production of hot tap water, only hot water is applied. The maximum temperature of water in internal installations amounts to 95°C because a higher

temperature is not admissible due to the fact that it would deteriorate the internal comfort (due to radiation of heaters and dry distillation of dust). As a heat carrier, steam is generally used for the purpose of supplying industrial consumers and also some complex buildings (e.g., hospitals).

5.3.3. Heat demand for space heating

In the steady state the heat demand for heating of the rooms is equal to heat losses through the external walls:

$$\dot{Q}_h = \sum_i A_i k_i (T_{in} - T_{ex}) \quad (5.1)$$

where:

$\dot{Q}_h$ - heat flux for heating,

A_i - the surface of external walls of building,

k_i - coefficient of heat transfer,

t_{in} - internal temperature,

t_{ex} - external temperature.

The temperature inside the rooms is determined in compliance with the respective building standards, usually amounting to 20°C in the case of living accommodations. The external temperature depends on atmospheric conditions, mostly presented in the form of a duration curve.

The heat demand for heating reaches its maximum when the temperature outside is at its lowest $T_{ex \min}$ characteristic for the given climatic zone:

$$\dot{Q}_{h \max} = \sum_i A_i k_i (T_{in} - T_{ex \min}) \quad (5.2)$$

Dividing both sides of Eqs.(5.1) by (5.2) and assuming that $k_i = \text{idem}$, we get the relation describing relative heat flux reduced representing the characteristics of the demand for heat:

$$\frac{\dot{Q}_h}{\dot{Q}_{h \max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min}} \quad (5.3)$$

Figure 5.1. presents the characteristics of the heat demand for heating purposes.

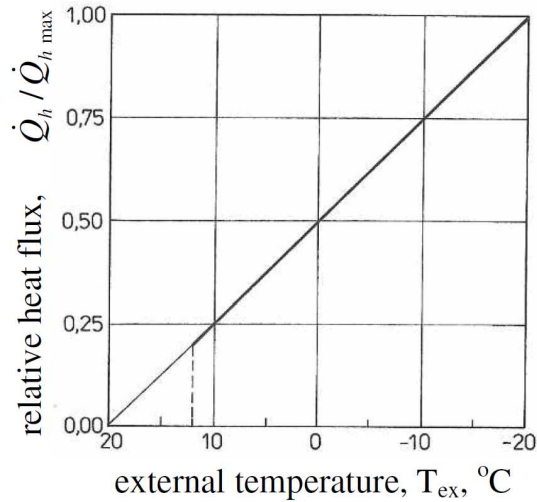


Fig.5.1. Heat flux for heating

The maximum heat demand for heating purposes is generally calculated based on the knowledge of the volume of the rooms to be heated and the unit losses of heat determined at ΔT characterising the maximum difference between the inside and minimum outside temperature ($T_{ex \min}$).

$$\dot{Q}_{h \max} = V\dot{q} \quad (5.4)$$

where:

V - volume of heated rooms,

$\dot{q}$ - unit losses of heat in external conditions,

The coefficient $\dot{q}$ also takes into account the heat losses due to the infiltration of air (natural ventilation).

5.3.4. Heat demand for ventilation

In housing estates the heat demand for natural ventilation is usually taken into account in calculations of the heat required for space heating. In the case of complex buildings and industrial buildings the heat demand for ventilation depends mainly on the category of consumers and often exceeds the heat demand for heating purposes.

A change of polluted air in complex buildings and industrial buildings is achieved by means of fans which suck in fresh air from outside, preheat it in heaters and press it into the room in an amount required for the purpose of changing the polluted air. This is called

mechanical ventilation. The heat flux required for mechanical ventilation is calculated by means of the equation:

$$\dot{Q}_v = mn_v (Mc_p) \Big|_{T_{ex}}^{T_{in}} (T_{in} - T_{ex}) \quad (5.5)$$

where:

$$n_v = \frac{p_{in} V_{in}}{(MR) T_{in}} \quad (5.6)$$

where:

p_{in}, T_{in} - pressure and temperature inside ventilated room,

V_{in} - volume (cubature) of ventilated rooms,

(MR) - universal gas constant,

m - multiplicity of the exchange of air per unit of time,

$(Mc_p) \Big|_{T_{ex}}^{T_{in}}$ - mean specific molar heat capacity at constant pressure within the range of the external and internal temperature.

The multiplicity m of the exchange of air is settled by special sanitary regulations. Applying Eq.(5.5) in the case of minimum external temperature, obligatory for ventilation and dividing it on both sides by Eq.(5.5) we get the characteristics of the heat demand for ventilation:

$$\frac{\dot{Q}_v}{\dot{Q}_{v \max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min v}} \quad (5.7)$$

In industrial plants in which production involves large amounts of noxious substances (dust and gases) the minimum external temperature $t_{ex \min}$ is assumed to be the same as for heating. In other cases, particularly in complex (public) buildings, where hygienic conditions permit, the minimum external temperature is assumed to amount to -5°C .

Figure 5.2 presents a diagram of the characteristics of heat demand for ventilation if the minimum external temperature of -5°C .

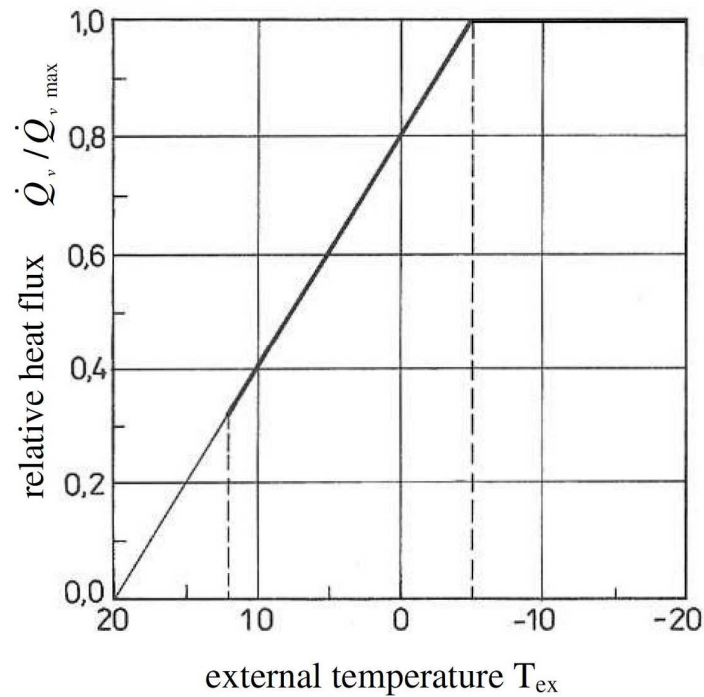


Fig 5.2.Heat flux for ventilation

In the temperature range -20°C to -5°C a smaller amount of air is heated. For this purpose the following methods of regulation are applied:

- setting ajar the throttles at the sucking orifices,
- reducing the number of revolutions of the fans,
- switching off some parallelly operating fans,
- recirculation of warm air.

If $T_{ex \min v} = T_{ex \min} = -20^{\circ}\text{C}$ the characteristic of the heat demand for ventilation purposes is the same as the characteristic of the heat demand for heating (Fig.5.1).

5.3.5. Heat demand for the production of hot tap water

Calculations concerning the heat demand for the production of hot tap water are based on its unit consumption quoted with respect to the standards obligatory for complex buildings, housing estates and industrial plants. The demand for hot tap water per day is calculated based on the relation:

$$\bar{G}_{htw} = nq_m \quad (5.8)$$

where:

$\overline{G}_{htw}$ - average daily demand for hot tap water,

n - number of consumers,

q_m - average calculated daily demand for hot tap water per person.

The flux of heat required to heat up tap water is calculated by means of the relation:

$$\dot{Q}_{htw} = \dot{G}_{htw} c_w (T_{htw} - T_w) \quad (5.9)$$

where:

$\dot{G}_{htw}$ - flux of hot tap water,

c_w - specific heat capacity of water,

T_{htw} - temperature of hot tap water,

T_w - temperature of tap water.

The temperature of hot tap water at the inlet to the buildings should not exceed 55°C due to the corrosion of zinc. If the installation consists of plastic, an increase in temperature of the hot tap water above 80°C accelerates the ageing of the material. In central Europe the mean temperature of tap water amounts in winter to 7-8°C and in summer to about 20°C [5].

Figure 5.3 provides an example of a 24-hour diagram illustrating the demand for hot tap water supplied to municipal consumers [5]. In order to minimise fluctuation in the consumption of hot tap water, hot water storages are applied.

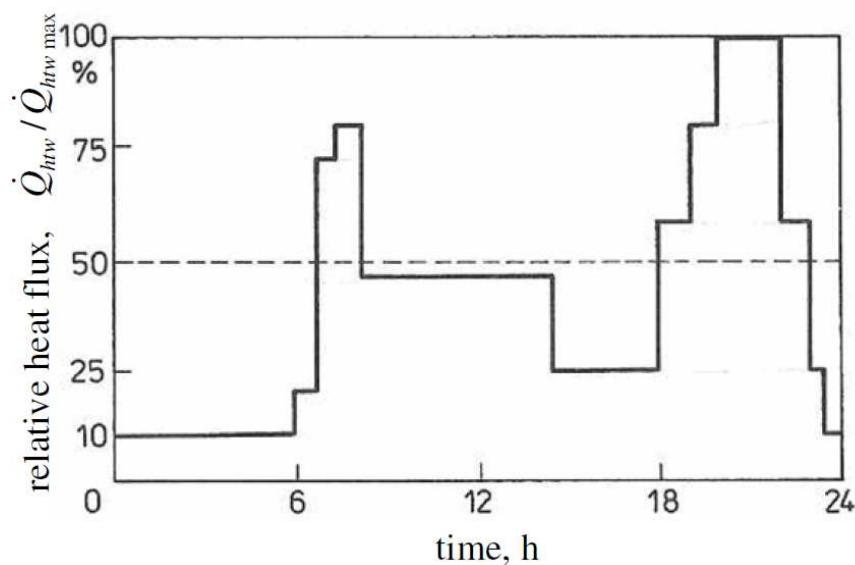


Fig.5.3.Exemplary demand for hot tap water in the case of municipal consumers adapted from Kamler [5]

5.3.6. Total demand for heat

Figure 5.4 presents, for the sake of an example, the way to construct a total duration curve of the heat demand for heating, ventilation and getting hot tap water [5]. As input data the duration curve of external temperature is assumed to take into account the climatic zone under consideration, as well as the maximum heat demand for heating and ventilation, because both mentioned fluxes of heat depend on the external temperature. The heat demand for heating and ventilation occurs in the heating season, whereas the heat demand for getting hot tap water is assumed to take the form of a double-step diagram presenting the demand for heat, respectively, during and beyond the heating season.

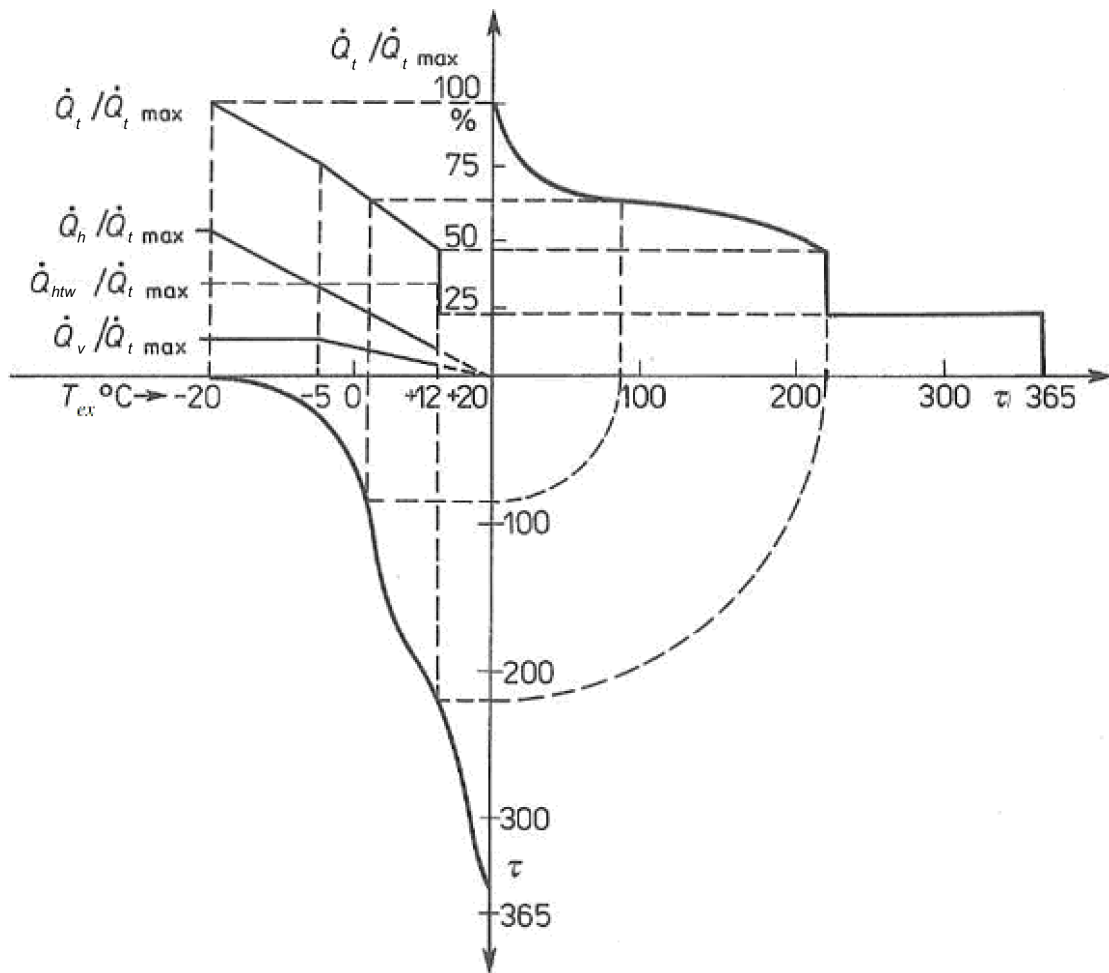


Fig. 5.4. Example of constructing the duration curve of the global heat demand for heating, ventilation and hot tap water adapted from Kamler [5]; $\dot{Q}_h$ - flux of heat required for space heating, $\dot{Q}_v$ - flux of heat for ventilation, $\dot{Q}_{htw}$ - flux of heat for getting hot tap water, $\dot{Q}_t$ - total flux of heat.

In order to find the total duration curve of the heat demand for space heating, ventilation and technological purposes (e.g., in complex buildings such as hospitals and rehabilitation centres) the method of composing duration curves must be applied [12], because the heat demand for technological purposes is independent of the external temperature. Thus the duration curves of the heat demand for heating and ventilation, on the one hand and that for technological purposes, on the other, ought to be treated as independent variables, applying the method of convolution of the distribution functions of random variables [12].

5.3.7. Choice of parameters of the heat carrier

As has already been mentioned, the following heat carriers are applied:

- hot water,
- steam with various parameters (e.g., in hospitals).

If heat is required merely for the purposes of heating, ventilation and hot tap water, only hot water is used. Hot water is the most appropriate agent for transporting heat at larger distances (up to a score of kilometres). The maximum parameters of water with respect to its supply and return must be determined by means of economic analysis, which again results from the following thermal analysis. The flux of heat $\dot{Q}_h$ may be expressed by means of the following relations:

a) with respect to its supply:

$$\dot{Q}_h = \dot{G}_w c_w (T_h - T_r) \quad (5.10)$$

where:

$\dot{G}_w$ - flux of network water,

c_w - specific heat capacity of water,

T_h - temperature of hot water,

T_r - temperature of return water.

b) with respect to consumers (direct connection):

$$\dot{Q}_h = A_h k_h \left(\frac{T_h + T_r}{2} - T_{in} \right) \quad (5.11)$$

where:

A_h - surface of heat transfer,

k_h - coefficient of heat transfer concerning heaters,

T_{in} - internal temperature.

Assuming that the temperature of hot water is constant (e.g., restricted by the pressure of heating steam in the heat exchanger) and that $\dot{Q}_h = idem$, the drop in the temperature of the return water is accompanied by a possible decrease of the water flux $\dot{G}_w$ (Eq.5.10) and thus also by a decreased diameter of the pipelines of district heating networks and decreased capital expenditures. On the other hand, however, the mean temperature of the heating agent also decreases, so that the surface of the heaters must be increased (higher capital expenditure) in order to transfer the same flux of heat. Both of these contrary factors determine the choice of the optimal values of the maximum temperature of hot water and return water.

Additional factors which ought to be taken into account in the choice of the optimal values of the temperature of hot water and return water are:

- power rating of the pumps and the consumption of electricity for the purpose of pumping the network water; the smaller the flux of pumping, the smaller are the power rating of the pumps and the consumption of electricity,
- losses occurring during the transport of heat; the higher the temperature of hot water and the return water the higher are the losses of heat,
- the cogeneration factor when heat is supplied from CHP plant; the lower temperature of hot water corresponds to a higher cogeneration factor.

Taking into account the aforesaid factors resulting from thermal analysis the maximum values of the temperature of hot and return water are determined by means of economic optimisation [10].

5.3.8. Thermal centres

The heat agent is supplied to the consumers (buildings and technical installations) by heating networks. Then it must be distributed to the respective installations (heating and ventilation systems, and technological heat exchangers). The installations are frequently adapted to other parameters than those of the external networks. The high thermal parameters of the external

networks are changed to lower parameters of the internal networks by means of thermal centres. A thermal centre comprises a set of segments of pipelines and thermal devices with pipe fittings and measuring instruments, from the cut-off valve of the external network to the valve cutting off the thermal centre from the internal installations.

The aims of the thermal centre are to:

- transfer heat from the external network to internal installations,
- initiate the circulation of the heating agent in the internal network,
- protect internal installations against increases in pressure exceeding the admissible value,
- reduce the temperature and pressure of the heating agent,
- retain the contaminations.

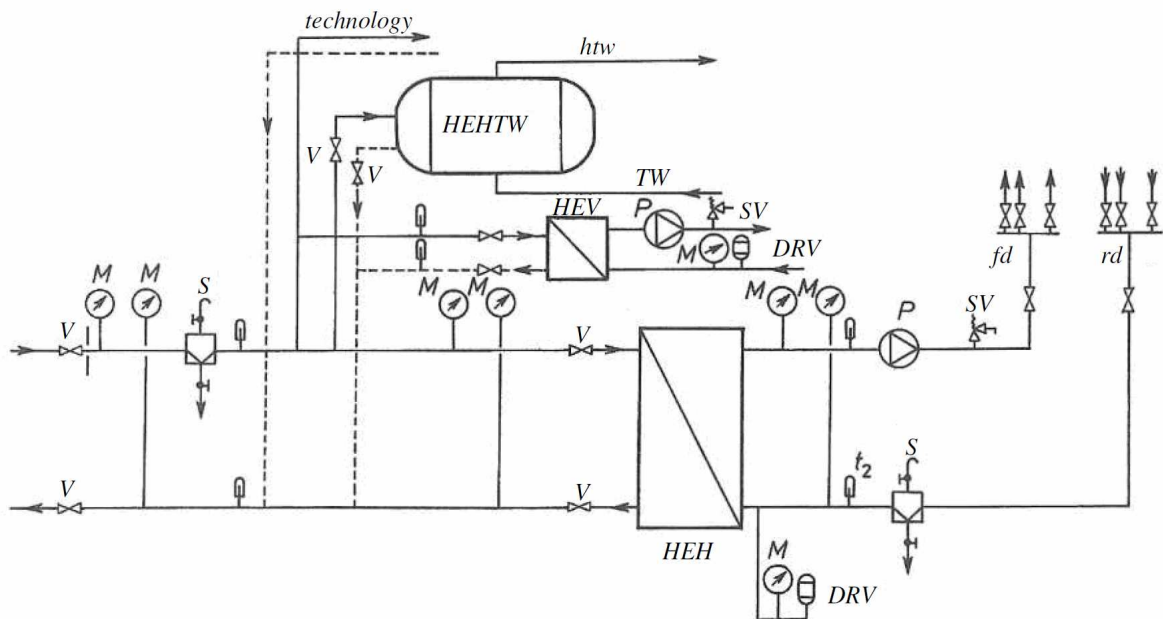


Fig.5.5. Scheme of a multi-functional thermal centre. Denotations: V-cut-off valve, M-manometer, S-sludger, SV-safety-valve, DRV-diaphragmatic rising vessel, T-thermometer, fd-feeding divider, rd-returned divider, P-circulating pump, HEHTW-heat exchanger for hot tap water, htw-hot tap water, TW-tap water, HEV-heat exchanger for ventilation, HEH-heat exchanger for central heating.

The following ways to connect the consumers of heat with district heating networks can be distinguished:

- direct low-parameter connection, when the thermal parameters of the heating agent supplied by the external network need not be reduced,
- direct connection by means of a jet pump, in which the parameters (temperature and pressure) of the water from the external networks are reduced,
- direct connection by means of pumps,
- indirect connection by means of heat exchangers, mainly of the type water/water, and rarely steam/water.

Direct thermal centres are nowadays rather rarely used and are displaced by indirect thermal centres, due to their drawbacks such as infiltration of contaminations into the internal installations, the necessity of maintaining an adequate disposable pressure in the thermal centre, and difficulties in warranting a stable hydraulic control.

Indirect thermal centres (Fig.5.5) are usually installed as two- or three- functional ones (heating and ventilation, as well as hot tap water) [5]. Mostly countercurrent heat exchangers are applied, either tubular or lamellar.

The standard equipment of the thermal centres comprises:

- sludger of network water,
- thermometers and manometers,
- heat exchangers,
- circulating pumps of heating water and hot tap water,
- controlling orifices,
- elements of automatics,
- heat meters.

In the thermal centres of hot tap water accumulating preheaters operate, included in the heating network either in series or in parallel.

5.3.9. Control of the supply of heat

The heat demand for heating and ventilation depends on the external temperature, and the heat demand for technological purposes (e.g., in hospitals) depends on the operating conditions of the technological devices. Therefore the supply of heat must be properly controlled.

Depending on the place where the control is realised we can distinguish:

- central control (concerning production),

- local control (in receivers or thermal centres).

Central control is applied when the thermal load of the heating network is homogeneous (e.g., merely heating). Local control is applied when the consumption varies (heating, ventilation and hot tap water).

The amount of heat Q transferred by thermal devices is expressed by the relation:

$$Q = Ak\Delta T\tau \quad (5.12)$$

where:

A - surface of heat transfer,

k - coefficient of heat transfer,

ΔT - mean difference of temperature,

τ - time.

Analysing the ways of controlling the mean arithmetic difference in the temperature may be applied:

$$\Delta T = \frac{T_h + T_r}{2} - \frac{T_1 + T_2}{2} \quad (5.13)$$

where:

T_h - temperature of hot water in external heating network,

T_r - temperature of returned water of external heating network,

T_1 - inlet temperature of water in internal heating network,

T_2 - outlet temperature of water in internal heating network.

Including Eqs.(5.10) and Eq.(5.13) into Eq.5.12 we get:

$$Q = \frac{T_h - \frac{1}{2}(T_1 + T_2)}{\frac{1}{Ak} + \frac{1}{2\dot{G}c_w}} \tau \quad (5.14)$$

Analysing the relation (5.14) five possibilities of control can be distinguished:

- local control by changing the surface of the receivers (partial switching off); rarely used, usually in technological installations,
- changing the heat transfer coefficient by changing the flow rate of the heating agent or the application of shields (local control),
- changing the temperature of hot water in the external heating network (qualitative central control),

- changing the flux of hot water in the external heating network (quantitative central control),
- changing the time of operation of the installations, introducing breaks in the operation (so-called pulsatory control); this kind of control is applied in interim periods in the case of a higher external temperature and the necessity of maintaining an adequate temperature of the feeding hot water in order to obtain hot tap water with a constant temperature.

In most cases qualitative control in the water heating network is applied. The advantages of such a control are:

- easy attendance and exploitation,
- the possibility of maintaining a lower temperature of the feeding water for a longer time (higher effects thanks to cogeneration due to the lower pressure of the heating steam).

A drawback of the qualitative control is the fact that it does not strictly meet the needs of all the consumers. Practically, in this system the temperature is adjusted to the needs of the dominant number of consumers. For the remaining consumers additional local control is applied.

The flux of heat transferred by the external heating network is expressed by the Eq.(5.10), based on which the methods of central control are defined, viz.:

- qualitative control- $G_w = idem$, $T_h, T_r = varia$,
- quantitative control- $G_w = varia$, $T_h = idem$, $T_r = varia$,
- hybrid quantitative- qualitative control.

Qualitative control, realised by maintaining a constant flow rate ($G_w = idem$), is characterised by keeping the hydraulic conditions of the heating networks stable. The third way of central control is applied in heating networks which supply heat and hot tap water in the heating season and only hot tap water in summer.

5.3.9.1. Qualitative control

Characteristics of the heating network in the case of supplying heat

Based on the Eqs.(5.1), (5.10), (5.11) concerning running conditions and minimum external temperature (maximum heating load), dividing both sides of them by themselves and assuming that the heat transfer coefficients k and k_h are constant, in the case of direct connection without mixing, we get:

$$\frac{\dot{Q}_h}{\dot{Q}_{h \max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min}} = \frac{T_h - T_r}{T_{h \max} - T_{r \max}} = \frac{\frac{1}{2}(T_h + T_r) - T_{in}}{\frac{1}{2}(T_{h \max} + T_{r \max}) - T_{in}} \quad (5.15)$$

hence

$$T_h = T_{in} + \frac{T_{h \max} - T_{in}}{T_{in} - T_{ex \min}} (T_{in} - T_{ex}) \quad (5.16)$$

$$T_r = T_{in} + \frac{T_{r \max} - T_w}{T_{in} - T_{ex \min}} (T_{in} - T_{ex}) \quad (5.17)$$

where:

T_{in} - internal temperature,

T_{ex} - running external temperature,

$T_{ex \min}$ - minimum external temperature,

$T_{h \max}$ - maximum temperature of hot water,

$T_{r \max}$ - maximum temperature of returned water.

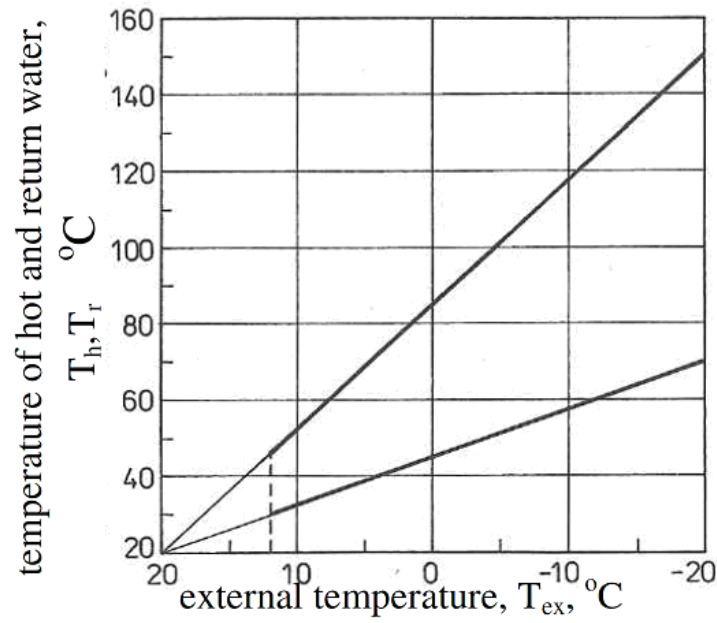


Fig. 5.6. Characteristics of heating network (qualitative control)

Figure 5.6 presents the characteristics of the heating network concerning heating loads according to (5.16) and (5.17), valid in the case of direct connections without mixing and assuming that the heat transfer coefficient for the heaters is constant.

In the case of indirect connections by means of a heat exchanger of the type water/water the energy balance equation is additionally applied and the relation determining the power rating of the heat exchanger is calculated in compliance with the method of thermal effectivity [9].

$$\dot{Q} = \dot{G}_w c_w (T_h - T_r) = \dot{G}_{hr} c_{hr} (T_1 - T_2) \quad (5.18)$$

$$\dot{Q} = \varepsilon \dot{W}_{\min} (T_h - T_r) \quad (5.19)$$

where:

$\dot{G}_{hr}$ - flux of water in installations of heat receivers,

c_{hr} - specific heat capacity of water in installation of heat receivers,

ε - effectivity of heat exchanger,

$\dot{W}_{\min}$ - smaller value of flux of heat capacity concerning water from external heating network and water in installation of heat receivers.

As far as the internal heating network is concerned, feeding the receiving installations, the Eqs.(5.16), (5.17) are valid for the qualitative control, whereby T_h and T_r are to be replaced respectively by T_1 and T_2 . Then, in the case of the external heating network based on the Eqs.(5.18), (5.19) and the characteristics of the internal heating network, the following equations concerning the temperature T_h , T_r of heat and return water are obtained:

$$T_h = T_{in} + \left[T_{2\max} - T_{in} + \frac{\dot{G}_{hr} c_{hr}}{\varepsilon \dot{W}_{\min}} (T_{1\max} - T_{2\max}) \right] \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\min}} \quad (5.20)$$

$$T_r = T_{in} + \left[T_{2\max} - T_{in} + \left(\frac{\dot{G}_w c_w}{\varepsilon \dot{W}_{\min}} - 1 \right) (T_{h\max} - T_{r\max}) \right] \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\min}} \quad (5.21)$$

These two equations are valid assuming that the heat transfer coefficients of the heaters are constant.

Characteristics of the heating network in the case of ventilation

Based on Eqs.(5.7) and (5.10) and the relations of the amount of heat transferred from the air heater:

$$\dot{Q}_v = \sum A_h k_h \left(\frac{T_h + T_r}{2} - \frac{T_{in} + T_{ex}}{2} \right) \quad (5.22)$$

expressing the running and extreme conditions and assuming that the heat transfer coefficients are constant, we get:

$$\frac{\dot{Q}_v}{\dot{Q}_{v\max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\max v}} = \frac{T_h - T_r}{T_{h\max} - T_{r\max}} = \frac{T_h + T_r - T_{in} - T_{ex}}{T_{h\max} + T_{r\max} - T_{in} - T_{ex\min v}} \quad (5.23)$$

hence in the range of varying heat consumption:

$$T_h = T_r + \frac{T_{h\max} - T_{in}}{T_{in} - T_{ex\min v}} (T_{in} - T_{ex}) \quad (5.24)$$

$$T_r = T_{in} + \frac{T_{r\max} - T_{in}}{T_{in} - T_{ex\min v}} (T_{in} - T_{ex}) \quad (5.25)$$

When $T_{ex} < T_{ex\min}$ the relations hold true:

$$\frac{\dot{Q}_v}{\dot{Q}_{v\max}} = 1 \quad (5.26)$$

hence taking into account (5.23) we get:

$$T_h = T_{h \max} \quad (5.27)$$

$$T_r = T_{r \max} \quad (5.28)$$

Figure 5.7 provides exemplary characteristics of the heating network in the case of ventilation.

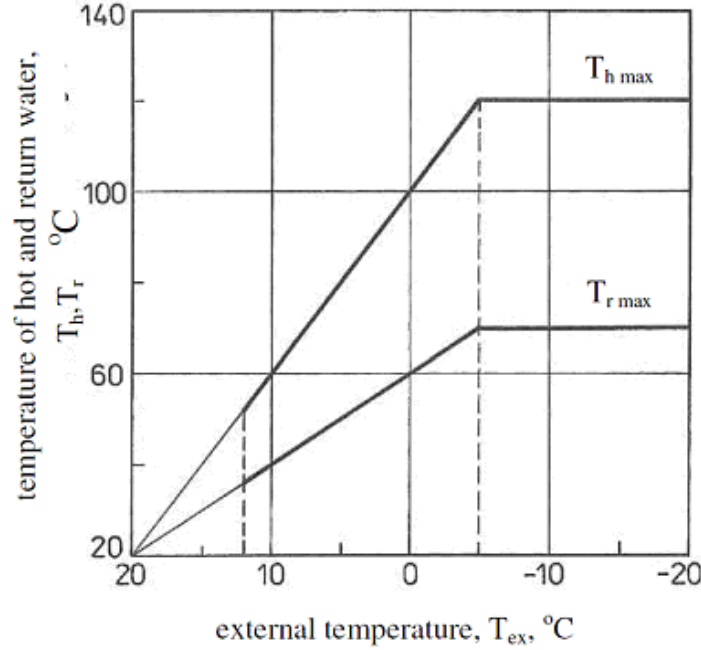


Fig.5.7. Characteristics of the heating network for ventilation (qualitative control)

5.3.9.2. Quantitative control

Characteristics of heat loads

The water flux is controlled by throttling its flow. The result of changing the flux of water is a change in the temperature of the return water. The set of equations that determine the characteristics of the heating network, based on the assumption that the coefficients of heat transfer are constant and that the consumers are connected directly without mixing, takes the form:

$$\frac{\dot{Q}_h}{\dot{Q}_{h \max}} = \frac{T_{in} - T_{ex}}{T_w - T_{ex \min}} = \frac{\dot{G}_w (T_{h \max} - T_r)}{\dot{G}_{w \max} (T_{h \max} - T_{r \max})} = \frac{\frac{1}{2} (T_{h \max} + T_r) - T_{in}}{\frac{1}{2} (T_{h \max} + T_{r \max}) - T_{in}} \quad (5.29)$$

where:

$\dot{G}_w$ - running flux of water in the heating network,

$\dot{G}_{w \max}$ - maximum flux of water in the heating network.

From the set of equations (5.29) we get:

$$T_r = 2T_{in} - T_{h \max} + (T_{h \max} + T_{r \max} - 2T_{in}) \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min}} \quad (5.30)$$

$$\frac{\dot{G}_w}{\dot{G}_{w \max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min}} \cdot \frac{T_{h \max} - T_{r \max}}{T_{h \max} - T_r} \quad (5.31)$$

Characteristics of ventilation loads

Assuming that the coefficient of heat transfer for heaters is constant and when the consumers are connected directly, we get in the case of a varying range of heat consumption:

$$\frac{\dot{Q}_v}{\dot{Q}_{v \max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex \min}} = \frac{\dot{G}_w}{\dot{G}_{w \max}} \frac{(T_{h \max} - T_r)}{(T_{h \max} - T_{r \max})} = \frac{(T_{h \max} + T_r) - (T_{in} + T_{ex})}{(T_{h \max} + T_{r \max}) - (T_{in} + T_{ex \min w})} \quad (5.32)$$

and hence:

$$T_r = (T_{in} + T_{ex}) - T_{h \max} + \frac{\dot{Q}_v}{\dot{Q}_{v \max}} [(T_{h \max} + T_{r \max}) - (T_{in} + T_{ex \min v})] \quad (5.33)$$

In the considered case a formula of analogical to (5.33) is valid, in which only $T_{ex \min}$ is replaced by $T_{ex \min v}$.

5.3.9.3. Hybrid control

Qualitative control is usually restricted to one kind of consumers (mainly for heating purposes). If there are various consumers (e.g., of heating and hot tap water) such a control is insufficient. When hot water is used for the production of hot tap water, its temperature must amount to at least 60÷70°C. Thus in the characteristics of the heating network two ranges of control are to be distinguished (Fig.5.8): qualitative and quantitative or pulsating control. The application of pulsating control is based on the cumulative ability of the rooms.

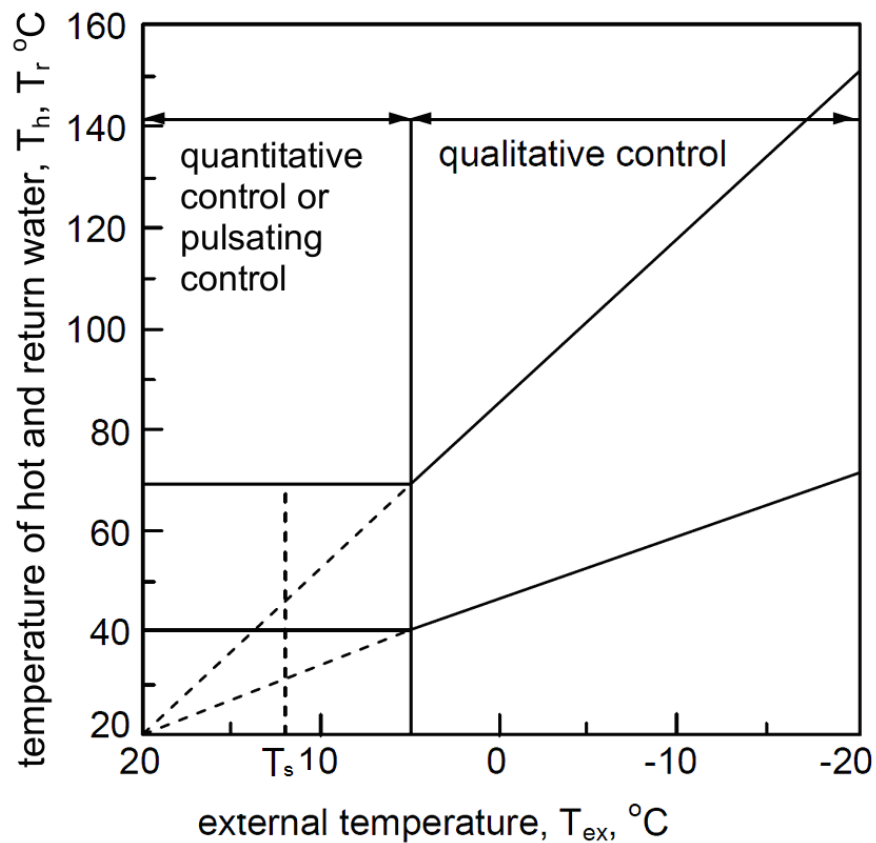


Fig.5.8. Characteristics of heating network in the case of hybrid control; T_s - temperature of the start of heating season

A quantitative-qualitative control of the heating network can be also realised by distinguishing several ranges of external temperature in the characteristics of the heating network [6]. An increase in the external temperature to the successive ranges corresponds to a decreasing flux of network water changing stepwise from range to range. Within each range qualitative control is being realised. This method of control is advantageous because the consumption of electrical energy for driving the pumps is reduced, but on the other hand it does not warrant a stability of hydraulic conditions in the heating network.

5.3.10. Application of heat pumps in heat engineering

Most often compression heat pumps driven by electrical energy are used. They can draw heat from the atmosphere, water reservoirs, the ground, warm sewage or solar collectors. Making use of the atmosphere is least effective because the heat demand for heating increases with a drop of the air temperature and simultaneously the COP (Coefficient of Performance) of the heat pump decreases. A large water reservoir (e.g., a lake) is a better bottom source of heat

thanks to its stable temperature under the cover of ice. Drawing heat from the ground is feasible when the temperature of the soil is higher than the temperature of the atmosphere. The best bottom sources of heat are resources of low-temperature waste energy (sewage and waste heat) and water preheated in solar collectors. The higher the temperature of the bottom source of heat, the higher is the COP.

The condition of energy effectiveness in the application of compression heat pumps takes the form [11]:

$$COP > \frac{\eta_{Eh}^*}{\eta_{Eel}^*} \quad (5.34)$$

where:

COP- Coefficient of Performance of a heat pump,

η_{Eh}^* - cumulative energy efficiency of heat production in a source replaced by a heat pump,

η_{Eel}^* - cumulative energy efficiency of electricity production.

In this equation the losses occurring in the course of transporting the heat from the heat pump have been neglected, and the cumulative investment component has not been taken into account.

The fact that energy effectivity has been satisfied does not mean that the application of an electrically driven compression heat pump is profitable, because its installation is connected with considerable expenditures, not only direct, but also additional expenditures, due to an increased power rating of the power station and electrical transmission grid. This is of essential importance in the case of thermal power plants. In the case of hydro-electric power plants it is less important.

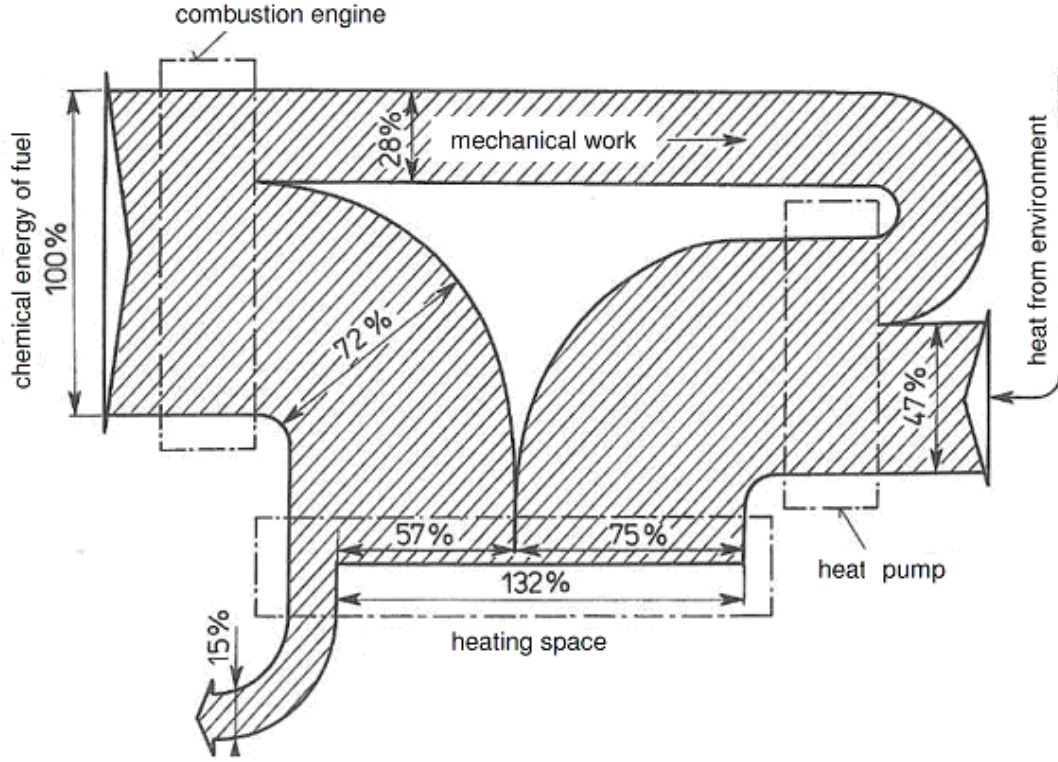


Fig.5.9. Band chart of the energy balance of a compression heat pump driven by an internal combustion engine [13]

The application of an internal combustion engine in the compression heat pump may improve the energy effectiveness because the heat produced by cooling the combustion engine and the physical enthalpy of flue gases are additionally utilised [13]. Figure 5.9 presents the band chart of the energy balance of a compression heat pump driven by an internal combustion engine. The energy effectiveness of a compression heat pump driven by a combustion engine may be expressed by the formula:

$$\varepsilon_{Eie} = \frac{\dot{Q}_h}{\dot{E}_{ch}} = COP \eta_{Eie} + (1 - \eta_{Eie}) \eta_{wh} \quad (5.35)$$

where:

$\dot{Q}_h$ - useful heat flux,

$\dot{E}_{ch}$ - chemical energy of fuel,

η_{Eie} - energy efficiency of internal combustion engine,

η_{wh} - energy efficiency of installation of waste heat recovery.

Assuming, for instance, that $COP = 2,7$; $\eta_{Eie} = 0,28$; $\eta_{wh} = 0,8$ we get $\varepsilon_{Eie} = 1,32$. The amount of heat supplied by the aggregate heat pump and internal combustion engine is

definitely greater than the used chemical energy of fuel. Besides the expenditures, the economic effectiveness of such a solution is influenced by the higher cost of liquid or gaseous fuels.

Also the application of an absorption heat pump can lower the threshold of energy effectivity. Assuming the losses of transferring heat from the heat pump and neglecting the cumulative investment component, the condition of the energy effectivity of applying absorption heat pumps takes the form:

$$COP > \frac{\eta_{Eh}^*}{\eta_{Ehd}^*} \quad (5.36)$$

where:

η_{Ehd}^* - cumulative energy efficiency of the production of heat driving the absorption heat pump.

The condition (5.36) is particularly easily satisfied when the replaced installation is a boiler house, which can simultaneously be the source of heating steam for the absorption heat pump. In this case the right-hand side of the inequality (5.36) approaches 1, and the COP for the absorption heat pump is evaluated as $\sim 1.1 \div 1.7$. When the replaced installation is a CHP plant, the condition (Eq.5.36) is much more difficult to be satisfied.

The energy effectivity of applying heat pumps can be improved by combining the heat pump with a refrigerator (cooling-heating cogenerating system), whereby heat is rather a by product [11].

5.4 Cogeneration of heat and electricity – Combined Heat and Power (CHP)

5.4.1. Thermodynamic motivation of benefits resulting from the realisation of heat-and-power cogeneration

The irreversibility of thermal processes can be decreased by combining them for the purpose of reducing the number of thermodynamic processes [10]. Simultaneously the emission of noxious substances to the environment can be reduced. Electricity and heat may be generated in separate processes, i.e., in the power station and in the heating plant. In a power station the cycle of the engine is realised. The heating plant may be considered as the cycle of a heat pump. Figure 5.10 presents irreversible cycles of the engine and heat pump [11]. Both of these individual cycles consist of isobaric processes of heat transfer from the working fluid to the environment. As the directions of heat transfer are with respect to the environment opposite to each other, the intermediate role of environment as a source of heat may be rejected. In this way we can eliminate two irreversible processes of heat transfer and consequently also the capital investment for heat exchangers. This can be achieved by shifting the upper isobar of the heat pump to the cycle of the engine, realising in this way a combined engine and heating cycle [11,12]. Thus, two irreversible processes of compression and expansion, realised in the cycle of the heat pump are also eliminated. Furthermore the ranges of irreversible compression and expansion in the cycle of the engine are reduced. The combined engine and heating cycle is shown in Figure 5.10b. This cycle is practically realised in CHP plants. Figure 5.11 presents the diagram of a classical CHP plant equipped with a back-pressure turbine.

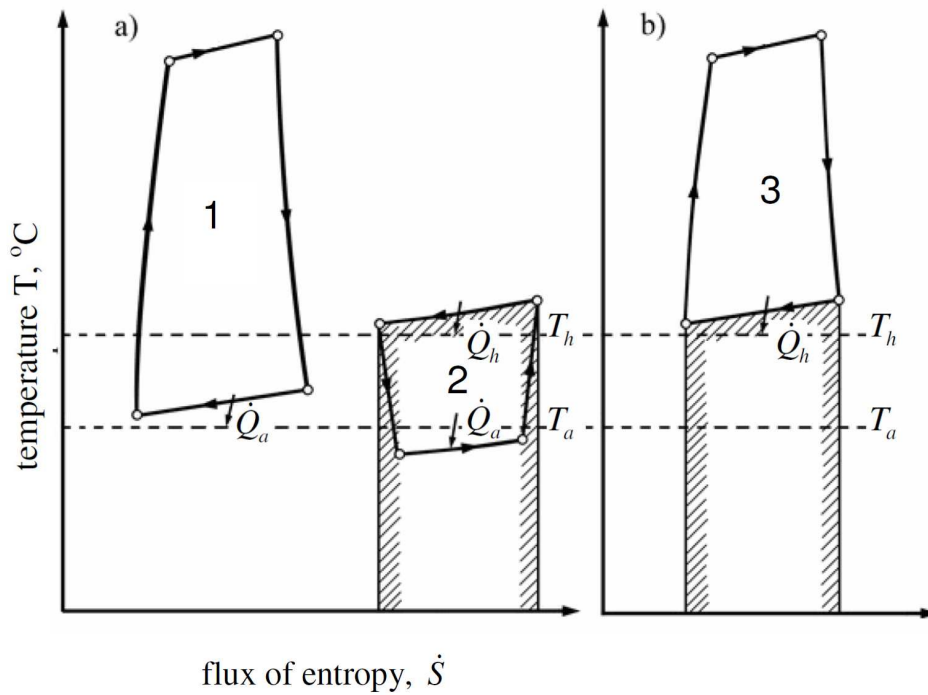


Fig. 5.10. The idea of a CHP plant [11]; $\dot{Q}_h$ - flux of heat for heating; $\dot{Q}_a$ - flux of heat exchanged between working fluid and environment, T_h - temperature of heating space, T_a - ambient temperature;
1- cycle of thermal engine; 2 – cycle of heat pump; 3 – cycle of CHP

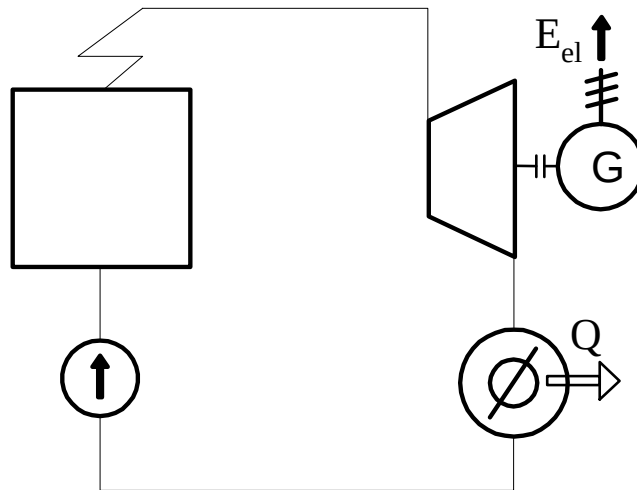


Fig.5.11 Classical CHP equipped with a back-pressure turbine

The second argument for cogeneration results from the comparison of the energy and exergy efficiencies of the boilers. Figure 5.12 presents a nomogram of the interdependence between the energy and exergy efficiency of steam boilers [16]. Boilers are characterised by the highest exergy losses of all elements of the power station. These losses can be reduced by

increasing the thermal parameters of live steam. In CHP plants the pressure and temperature of live steam are much higher than the thermal parameters in boilers of heating plants, particularly those plants equipped with water heater boilers. In this way we can decrease exergy losses thanks to the realisation of combined heat and electricity production.

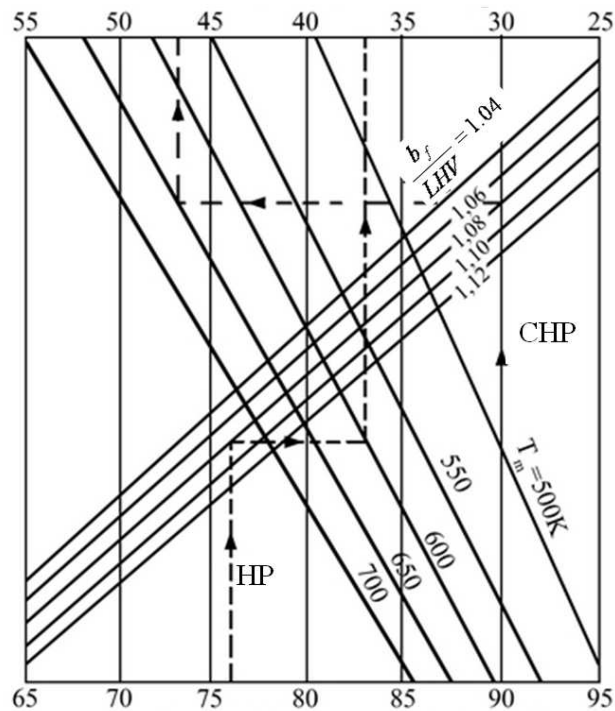


Fig. 5.12. Energy and exergy efficiency of a steam boiler;
CHP- cogeneration, HP – heating plant, b_f – exergy of fuel, T_m – thermodynamic average temperature (Appendix C)

The third thermodynamic argument for cogeneration is the possibility of a partial compensation of heat losses while transporting the heat. Figure 5.13 presents duration curves of the net and gross heat demand. Assuming that the share of cogeneration amounts to 0.6 we see the area of the cogeneration part and the area of the non-cogeneration part of a CHP (e.g., water heater boiler). In the range of peak loads the transportation losses of heat are covered by non-cogeneration installations, whereas at lower loads the compensation of the transportation losses of heat is achieved by increasing the production of heat in cogeneration. An increase in the production of heat in the cogeneration process due to heat losses affects the increase of electricity production and the growth of the useful effects of cogeneration. In this way the heat losses can be partially compensated.

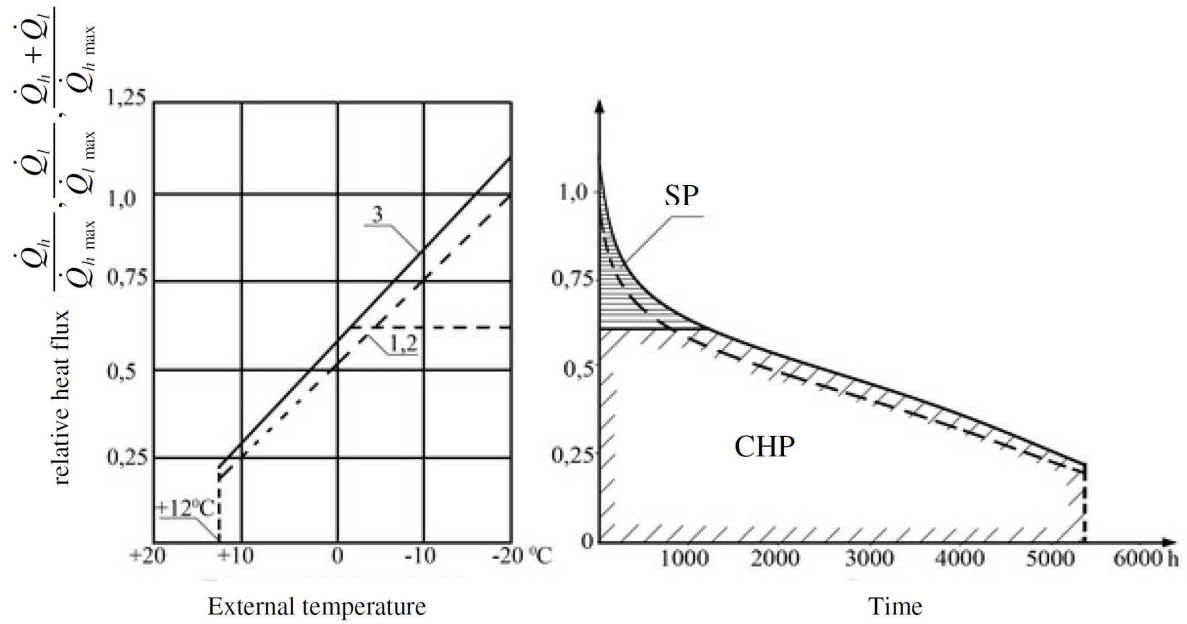


Fig. 5.13. The effect of heat losses on the characteristics of heat load and duration curve of heat demand: 1 – relative net heat load, 2 – relative losses of heat transport, 3 – relative gross heat load, SP – devices of separate heat production (pressure reducing valve or water heater), CHP- cogeneration

5.4.2. Energy effects of heat-and-power cogeneration in CHP plants

Savings in the chemical energy of fuel are determined by comparing its consumption in heating plants and power stations operating separately with its consumption in CHP plants. This comparison is carried out based on the assumption that the demands for heat and electricity by the consumers are the same in both cases of production:

$$Q_0 = idem \quad \text{and} \quad E_{el0} = idem$$

where:

Q_0 - demand for heat by consumers,

E_{el0} - demand for electricity by consumers.

The consumption of the chemical energy of fuel in the former case is the sum of its consumption in the heating plant and power station:

$$E_{chs} = \frac{Q_0}{\eta_{Ehp} \eta_{ht}} + \frac{E_{el0}}{\eta_{Epp} \eta_{et}} \quad (5.37)$$

where:

η_{Ehp} - net energy efficiency of heating plants,

η_{Epp} - net energy efficiency of power plant,

η_{ht} - energy efficiency of heat transmission,

η_{et} - energy efficiency of electricity transmission.

In the latter case the consumption of the chemical energy of fuel results from the equation:

$$E_{ch\ CHP} = \frac{1}{\eta_{E\ CHP}} \left[\frac{Q_0}{(1-\varepsilon_h)\eta_{ht}} + \frac{E_{el\ 0}}{(1-\varepsilon_{el})\eta_{et}} \right] \quad (5.38)$$

where:

$\eta_{E\ CHP}$ - gross energy efficiency of CHP ($\eta_{E\ CHP} = EUF$ [3]),

EUF - Energy Utilisation Factor,

η_{ht} - energy efficiency of heat transmission,

η_{et} - energy efficiency of electricity transmission,

$\varepsilon_h, \varepsilon_{el}$ - indices of own consumption of heat and electricity.

Savings of the chemical energy of fuels achieved by heat-and-power cogeneration is determined by the following formula:

$$-\Delta E_{ch} = Q_0 \left[\frac{1}{\eta_{E\ hp}\eta_{ht}} - \frac{1}{\eta_{E\ CHP}(1-\varepsilon_h)\eta_{ht}} \right] + E_{el\ 0} \left[\frac{1}{\eta_{E\ pp}\eta_{et}} - \frac{1}{\eta_{E\ CHP}(1-\varepsilon_{el})\eta_{et}} \right] \quad (5.39)$$

Assuming that the efficiency of heat and electricity transmission is the same in both cases and dividing equation (5.39) by the gross amount of heat, we get:

$$\frac{-\Delta E_{ch}}{Q} = \left[\frac{1}{\eta_{E\ hp}} - \frac{1}{\eta_{E\ CHP}(1-\varepsilon_h)} \right] (1-\varepsilon_h) + \sigma \left[\frac{1}{\eta_{E\ pp}} - \frac{1}{\eta_{E\ CHP}(1-\varepsilon_{el})} \right] (1-\varepsilon_{el}) \quad (5.40)$$

in which the coefficient of the cogeneration (ratio of electricity to heat produced in cogeneration) is:

$$\sigma = \frac{E_{el}}{Q} \quad (5.41)$$

where Q and E_{el} denotes gross production of heat and electricity in CHP plant.

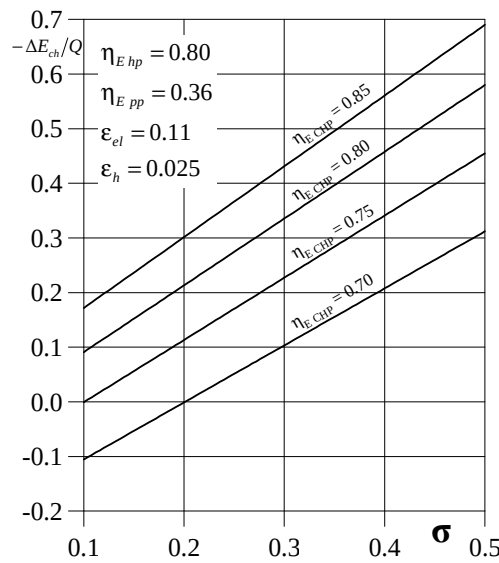


Fig. 5.14. Index of the saving of chemical energy of fuel

Figure 5.14 presents the dependence of the saving index of the chemical energy of fuel on the coefficient of cogeneration and gross energy efficiency of the CHP. The diagram in Figure 5.14 shows, for instance, that if 100 MW of heat are produced in a CHP plant with the efficiency $\eta_{E\text{ CHP}} = 0.85$ and the coefficient of cogeneration $\sigma = 0.4$, we may expect savings in the chemical energy of fuel to be about 56 MW.

5.4.3. The share of the fuel consumption in the production of heat and the production of electricity

The division of the consumption of the chemical energy of fuel in CHP between the production of heat and the production of electricity is connected with the determination of the partial efficiencies of heat and electricity production. In order to determine these partial efficiencies in the cogeneration process the method of avoided expenditure of fuels is applied. This is the same idea as the method of avoided cost being applied to divide the costs [10,11]. This method is also called *method of a replaced process*. Electricity produced as a by-product replaces partially the electricity from system power stations. Therefore the production of electricity in CHP plants should be charged at the same rate as the consumption of chemical energy of fuel as in the replaced (reference) power station. The term “replaced” should from the viewpoint of Directive on the promotion of cogeneration [1] be understood as a reference power station. The partial gross efficiency $\eta_{E\text{ el CHP}}$ of the production of electricity in CHP plants are determined based on the relation:

$$\eta_{E\text{ el CHP}} = \frac{N_{\text{el cog}}}{(\dot{P}LHV)_{\text{el CHP}}} \quad (5.42)$$

where:

$N_{\text{el cog}}$ - electrical power in cogeneration,

$\dot{P}LHV_{\text{el CHP}}$ - consumption of the chemical energy of fuel burdening electricity production.

Power replaced in a system power plant results from the condition of equality of the electrical power reaching the consumer:

$$\bar{N}_{\text{el CHP (lo)}} = \bar{N}_{\text{el pp (lo)}} \quad (5.43)$$

where:

$\bar{N}_{\text{el CHP (lo)}}$ - electrical power from CHP (reaching the consumers),

$\bar{N}_{\text{el pp (lo)}}$ - electrical power from power plant (reaching the consumers).

Relation (5.43) may also be expressed as:

$$N_{\text{el CHP}}(1 - \varepsilon_{\text{el}})\eta_{\text{et}} = N_{\text{el pp}}\eta'_{\text{et}} \quad (5.44)$$

where $N_{\text{el pp}}$ denotes the net electrical power of the power plant.

Applying the method of avoided input energy we get the relation:

$$(\dot{P}LHV)_{\text{el CHP}} = \frac{N_{\text{el pp}}}{\eta_{E\text{ pp}}} \quad (5.45)$$

Substituting the relations (5.44) and (5.45) in Eq. (5.42) we get:

$$\eta_{E\ el\ CHP} = \eta_{E\ pp} \frac{\eta'_{et}}{(1 - \varepsilon_{el})\eta_{et}} \quad (5.46)$$

The partial gross efficiency of heat production in cogeneration results from the equation:

$$\eta_{E\ h\ ec} = \frac{\dot{Q}_{CHP}}{(\dot{P}\ LHV)_{CHP} - N_{el\ CHP} \frac{(1 - \varepsilon_{el})\eta_{et}}{\eta_{E\ pp}\eta'_{et}}} \quad (5.47)$$

where:

$\dot{Q}_{CHP}$ - production of heat flux in cogeneration,

$(\dot{P}\ LHV)_{CHP}$ - consumption of the chemical energy of fuel in a CHP plant.

Equation (5.47) may be transformed as follows:

$$\eta_{E\ h\ CHP} = \frac{\eta_{E\ CHP}}{1 - \sigma \left[\frac{\eta_{E\ CHP}\eta_{et}(1 - \varepsilon_{el})}{\eta_{E\ pp}\eta'_{et}} \right]} \quad (5.48)$$

$$\eta_{E\ CHP} = \frac{\dot{Q}_{CHP} + N_{el\ CHP}}{PLHV_{CHP}} = EUF \quad (5.49)$$

As $\eta_{E\ CHP} > \eta_{E\ pp}$, the partial efficiency of heat production in a CHP is higher than the total efficiency of the cogeneration process. The higher the values of the cogeneration index, the higher also are the values of the partial efficiency of heat production. Thus it is energetically feasible to increase the parameters of live steam and decrease the pressure of the bleeding steam. The partial energy efficiency of heat production may attain values exceeding 1.

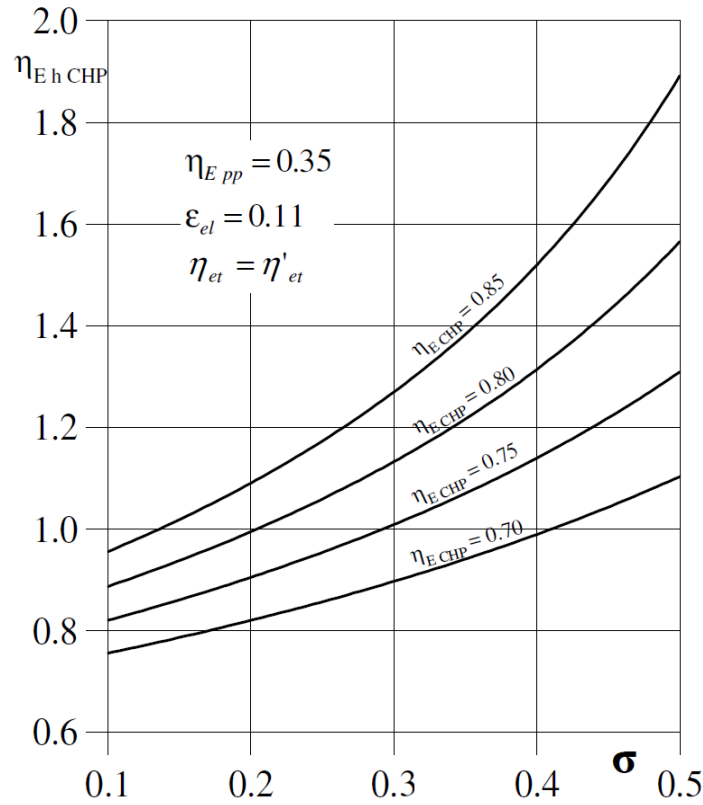


Fig. 5.15. Partial energy efficiency of heat production in a CHP plant

Such a result is physically correct because the CHP cycle results from the combined cycle of the heat engine with a heating pump whose energy efficiency is always higher than 1 [11].

5.4.4. Ecological effects of cogeneration

Savings in the chemical energy of fuels attained thanks to cogeneration result in a decreased emission of noxious substances. The emission of the i -th noxious substance caused by the independent production of heat and electricity is:

$$S_{is} = \frac{Q_0}{\eta_{ht} \eta_{Ehp} LHV_{hp}} e_{ihp} + \frac{E_{el0}}{\eta_{et} \eta_{Epp} LHV_{pp}} e_{ipp} \quad (5.50)$$

where:

S_{is} - emission of the i -th noxious substance in the case of separate production of heat and electricity,

e_{ihp} - index of the i -th noxious substance emission in heating plant,

e_{ipp} - index of the i -th noxious substance emission in power plant,

LHV_{hp}, LHV_{pp} - lower calorific value of fuel in heating plant and power plant, respectively.

The emission of the i -th noxious substance in a CHP plant results from the relation:

$$S_{iCHP} = \frac{1}{\eta_{E CHP} LHV_{CHP}} \left[\frac{Q_0}{\eta_{ht}(1-\varepsilon_h)} + \frac{E_{el0}}{\eta_{et}(1-\varepsilon_{el})} \right] e_{iCHP} \quad (5.51)$$

where:

$e_{i\text{ CHP}}$ - index of i-th noxious substance emission in CHP,

LHV_{CHP} - lower calorific value of fuel in CHP plant.

Assuming that the efficiencies of the transmission of heat and electricity are the same in the case of separate production of heat and electricity as in the CHP and that the LHV is the same, we obtain the following equation related to a unit of heat:

$$-\frac{\Delta S_i}{Q} = \frac{1}{LHV} \left[\frac{e_{i\text{ hp}}}{\eta_{E\text{ hp}}} - \frac{e_{i\text{ CHP}}}{\eta_{E\text{ CHP}}(1-\varepsilon_h)} \right] (1-\varepsilon_h) + \sigma \left[\frac{e_{i\text{ pp}}}{\eta_{E\text{ pp}}} - \frac{e_{i\text{ CHP}}}{\eta_{E\text{ CHP}}(1-\varepsilon_{\text{CHP}})} \right] (1-\varepsilon_{\text{CHP}}) \quad (5.52)$$

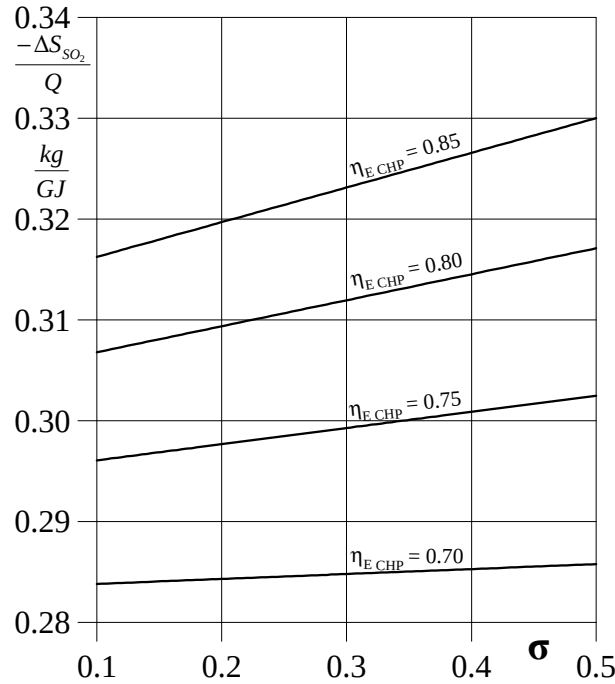


Fig. 5.16. Reduction of SO2 emission

The ecological effects of cogeneration depend not only on saving the chemical energy of fuel but also on the emission coefficients in both the separate production of heat and electricity and CHP plants. Figure 5.16 presents, for example, a decreased SO₂ emission.

5.4.5. Realisation of cogeneration by adapting the power unit to heat production [10], [14]

The adaptation of power units for the production of heat leads to cogeneration and to savings in the chemical energy of fuels. Keeping the consumption of the chemical energy of fuel at a constant level, the production of electricity is reduced due to the production of heat. This decrease in electricity production can be compensated by the additional production of electricity in a replacing power station. Figure 5.17 presents a diagram of the separate production of heat and electricity: heating plant and power station. In Figure 5.18 we have a diagram of a power unit adapted to the production of heat.

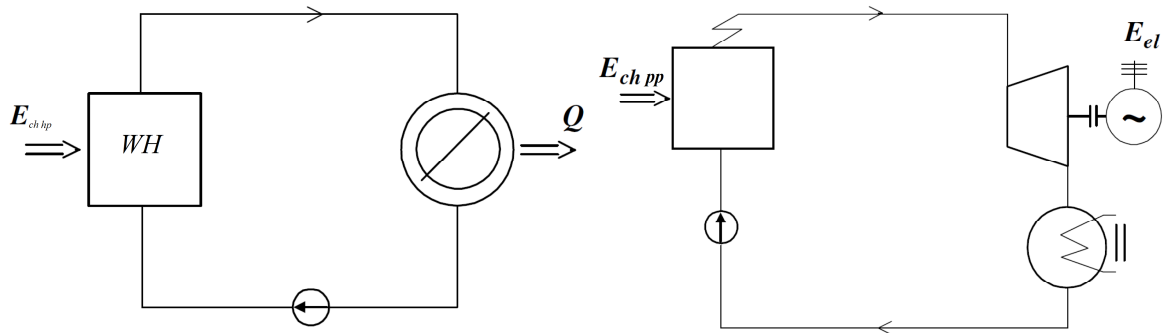


Fig. 5.17. Separate production of heat and electricity

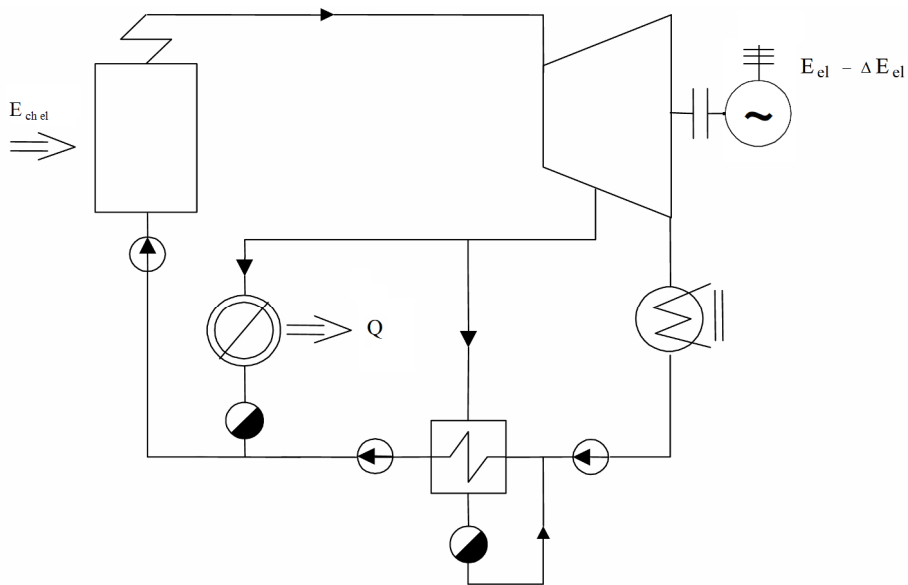


Fig. 5.18. Power plant after its adaptation to heat production; WH - water heater

The consumption of chemical energy in the case of separate production is expressed by the equation:

$$E_{ch s} = E_{ch pp} + E_{ch hp} \quad (5.53)$$

where:

$E_{ch pp}$ - consumption of chemical energy of fuel concerning the power unit before adaptation,

$E_{ch hp}$ - consumption of chemical energy of fuel concerning the heating plant.

The consumption of the chemical energy of fuel in a cogeneration system looks like that:

$$E_{ch cog} = E_{ch pp} + \Delta E_{ch r} \quad (5.54)$$

where $\Delta E_{ch r}$ denotes the consumption of chemical energy of fuel in a replacing power plant in which the decrease of electricity is compensated.

From the equations (5.53) and (5.54) we get the relation of savings $-\Delta E_{ch}$ of the chemical energy of fuels caused by the adaptation of a power unit to heat production:

$$-\Delta E_{ch} = \frac{Q_0}{\eta'_{ht} \eta_{E\ hp}} - \frac{\Delta E_{el}}{\eta_{E\ pp}} \quad (5.55)$$

where:

Q_0 - demand of heat (loco consumer),

η'_{ht} - energy efficiency of heat transmission in the case of a heating plant,

$\eta_{E\ hp}$ - energy efficiency of the heating plant,

$\eta_{E\ pp}$ - net energy efficiency of the replaced power plant,

ΔE_{el} - production of electricity in replaced power plant equal a decrease in electricity production concerning power unit adapted for heat production.

In the analysis the ratio of the reduction of electricity production to the amount of heat obtained from an adapted power unit is introduced. This relation is also called *coefficient of power decrease of the turbogenerator*:

$$u = \frac{-\Delta E_{el}}{Q_0} \eta_{ht} \quad (5.56)$$

where η_{ht} denotes the efficiency of heat transmission concerning the power plant adopted for heat production.

If Eq.(5.55) is transformed by dividing both sides by Q and applying relation (5.56) we get:

$$-\frac{\Delta E_{ch}}{Q} = \frac{\eta_{ht}}{\eta'_{ht} \eta_{E\ hp}} - \frac{u}{\eta_{E\ pp}} \quad (5.57)$$

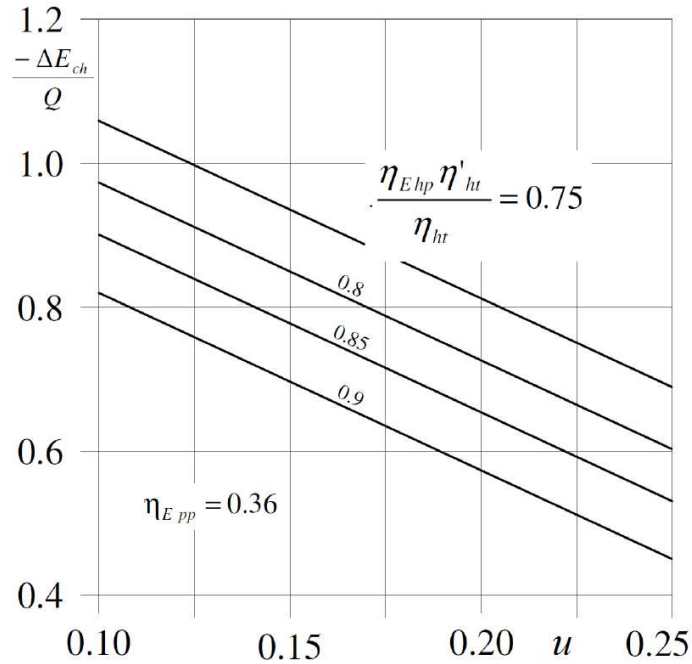


Fig. 5.19. Savings in the chemical energy of fuel due to adapting the power plant to the production of heat

Figure 5.19 shows relation (Eq.5.57) as a function of the coefficient of power decrease assuming as a parameter the expression $\frac{\eta_{E\ hp}\eta_{ht}}{\eta_{ht}}$. Savings in the chemical energy of fuel

achieved by adapting the power unit to the production of heat is higher, the lower the coefficient u , which means the lower the pressure of steam used for heating purposes and the lower the efficiency of the heating plant. If, for instance, the heating plant efficiency amounts to 0.85 and $u = 0.15$, we get $-\Delta E_{ch}/Q = 0.7$, which means that at 100 MW of the heat flux we save about 70 MW of the flux of chemical energy of the fuels.

As a result of the adaptation of the power unit for heat production the electricity production drops and must be compensated by the production of electricity in the replacing power station. Thus the production of heat in a power unit adapted for the production of heat ought to be charged at the same rate as the consumption of the chemical energy of fuel as in the replacing power station. Thus:

$$\eta_{E\ h\ pp} = \frac{Q}{\Delta E_{el}} \eta_{E\ pp} \quad (5.58)$$

or

$$\eta_{E\ h\ pp} = \frac{\eta_{E\ pp}}{u} \quad (5.59)$$

where $\eta_{E\ h\ pp}$ denotes the partial efficiency of heat production in the power station adapted to heat production.

In the case of the most often encountered values $u = 0.15$ and $\eta_{E\ pp} = 0.36$, the partial efficiency of heat production amounts to $\eta_{E\ h\ el} = 2.4$. As mentioned above, this result is physically correct because of the idea of cogeneration. The lower the effect of decreasing the electricity production due to the production of heat, the higher is the value of the partial efficiency of heat production.

Ecological effects

Savings in the chemical energy of fuel attained thanks to the adaptation of a power unit for the production of heat causes a decrease in the emission of noxious substances into the environment:

$$-\Delta S_i = S_{i\ hp} - \Delta S_{i\ pp} \quad (5.60)$$

where:

$S_{i\ hp}$ - emission of the i -th noxious substance concerning the heating plant,

$\Delta S_{i\ pp}$ - increase of the i -th noxious substance emission in the replacing power plant.

The emission of the i -th noxious substance is in the case of a heating plant expressed by the relation:

$$S_{i\ hp} = \frac{Q_0}{\eta_{ht}\eta_{E\ hp}LHV_{hp}} \sigma_{i\ hp} \quad (5.61)$$

where:

$\sigma_{i\ hp}$ - unit emission of the i -th noxious substance concerning heating plant,

LHV_{hp} - lower calorific value of fuel in a heating plant..

The increase of the emission of the i-th noxious substance in a replaced power plant results from the relation:

$$\Delta S_{i\ pp\ s} = \frac{\Delta E_{el}}{\eta_{E\ pp} LHV_{pp}} \sigma_{i\ pp} \quad (5.62)$$

where:

$\sigma_{i\ pp}$ - unit emission of the i-th noxious substance concerning power plant,

LHV_{pp} - lower calorific value of fuel in power plant.

Substituting Eqs. (5.61), (5.62) into Eq. (5.60) and taking into account the relation (5.56), and dividing both side by $Q = Q_0/\eta_{ht}$ we get:

$$-\frac{\Delta S_i}{Q} = \frac{\eta_{ht} \sigma_{i\ hp}}{\eta'_{ht} \eta_{E\ hp} LHV_{hp}} - \varepsilon \frac{\sigma_{i\ pp}}{\eta_{E\ pp} LHV_{pp}} \quad (5.63)$$

Assuming the following data: $\sigma_{SO_2} = 8.5$ g/kg fuel; $\sigma_{SO_2\ pp} = 1.6$ g/kg fuel; $LHV_{hp} = LHV_{pp} = 23$ MJ/kg; $\eta_{ht} = 0.89$; $\eta'_{ht} = 0.85$; $\eta_{E\ hp} = 0.85$; $\eta_{E\ pp} = 0.36$ a diagram of the relation $-\Delta S_i/Q$ as a function of ε has been plotted.

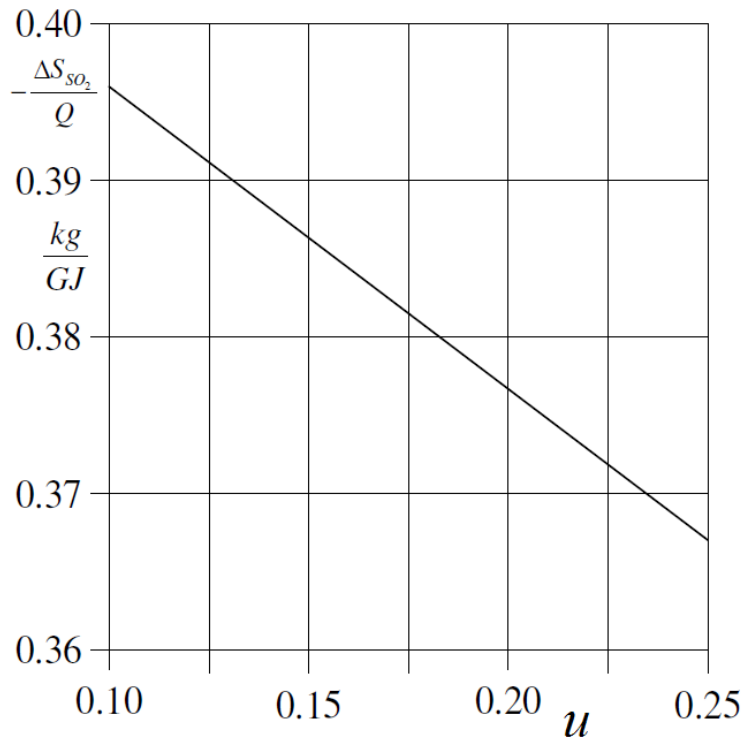


Fig. 5.20. Decrease in SO_2 emission due to adapting the power plant to the production of heat

5.4.6. Gas and gas-and-steam CHP units

A simple gas CHP unit consists of a gas turbine and a heat recovery boiler used to heat the network water (Fig.5.21) [10] . The combustion chamber is fed with compressed natural gas from the gas grid and with compressed air. The energy efficiency of the heat recovery boiler is high because the temperature of the flue gases leaving the heat recovery boiler may be only slightly higher than the temperature of the network return water. The exergy efficiency of the heat recovery boiler is, however, much lower due to the considerable difference between the temperature of the flue gases and the temperature of the network water which leads to considerable losses of exergy. The application of flue gas for the purpose of preheating network water considerably improves the energy efficiency of the cogeneration system if compared with the open cycle of the gas turbine, but the improvement in exergy efficiency is much lower.

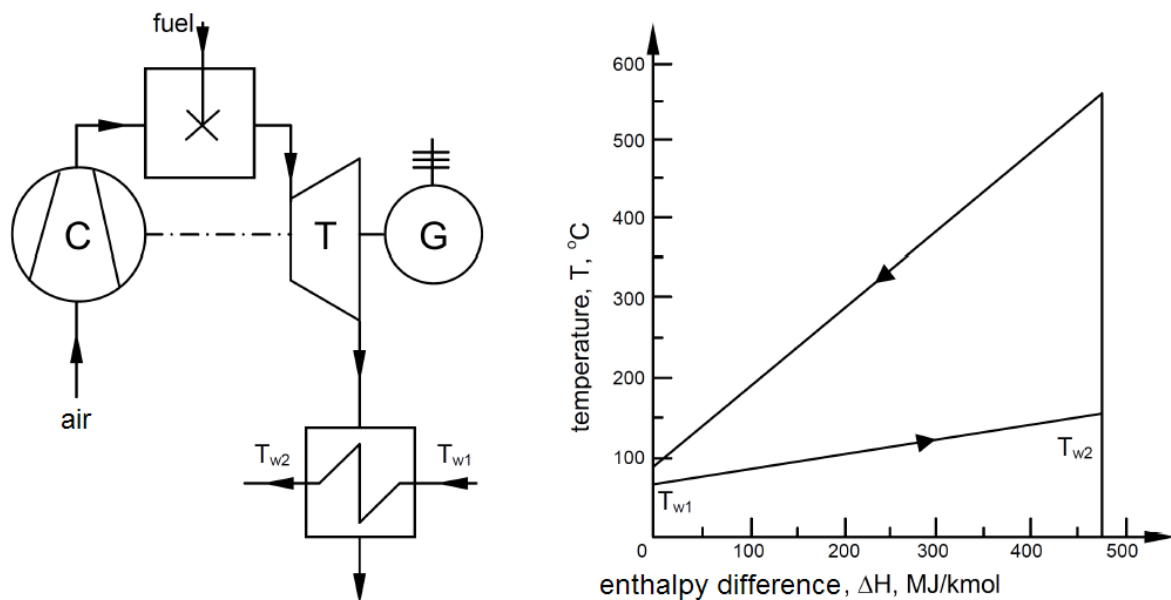


Fig. 5.21. Scheme of a simple gas CHP unit and temperature distribution in heat recovery boiler [10]; C - compressor; T - gas turbine, G - generator; T_{w1} , T_{w2} - temperature of network water

$$\eta_{BCHP} = \frac{E_{el} + Q \frac{T_m - T_a}{T_m}}{a LHV} = \eta_{BCHPg} + \Delta\eta_B \quad (5.64)$$

$$\Delta\eta_B = \frac{Q}{a LHV} \cdot \frac{T_m - T_a}{T_m} \quad (5.65)$$

where:

η_{BCHP} - exergy efficiency of CHP unit,

E_{el} - production of electricity,

Q - production of heat,

T_m - thermodynamic average temperature (Appendix C),

T_a - ambient temperature,

a - ratio of chemical exergy of fuel to LHV,

LHV - lower heating value,

η_{Bg} - electrical efficiency of gas turbine cycle,

$\Delta\eta_B$ - increase in exergy efficiency thanks to preheating of network water.

The exergy efficiency of a simple gas CHP unit can be improved by preheating the compressed air by high-temperature flue gases leaving the gas turbine. Only after leaving the preheater of compressed air the flue gases are used to preheat the network water. This solution is, however, much more expensive due to the high expenditure needed for the high-temperature preheater of compressed air. Another way of improving the exergy efficiency of a gas CHP unit is to utilise high-temperature flue gases for so-called chemical recuperation consisting in the application of flue gases for the conversion of methane contained in natural gas. As the exergy of flue gases is applied for the production of heat only in the range of a reduced temperature of the flue gases, the ratio of the electrical power to the heating power is in this system higher than in a simple gas CHP [10].

The exergy efficiency of a simple gas CHP unit can be improved by utilising the high-temperature flue gases leaving the turbine for the production of steam in the heat recovery steam generator, and for driving the steam turbine. Figures 5.22 and 5.23 [10] present the scheme of a single-pressure steam-and-gas CHP unit and temperature distribution in the heat recovery steam generator. A drawback of this solution is that there are considerable exergy losses in the evaporator. Therefore this solution is usually realised only in small-scale CHP

plants (e.g., in complex buildings). The ratio of the electrical power to the heating power may reach the value of about 1, whereas in a steam CHP plants it amounts to 0.45.

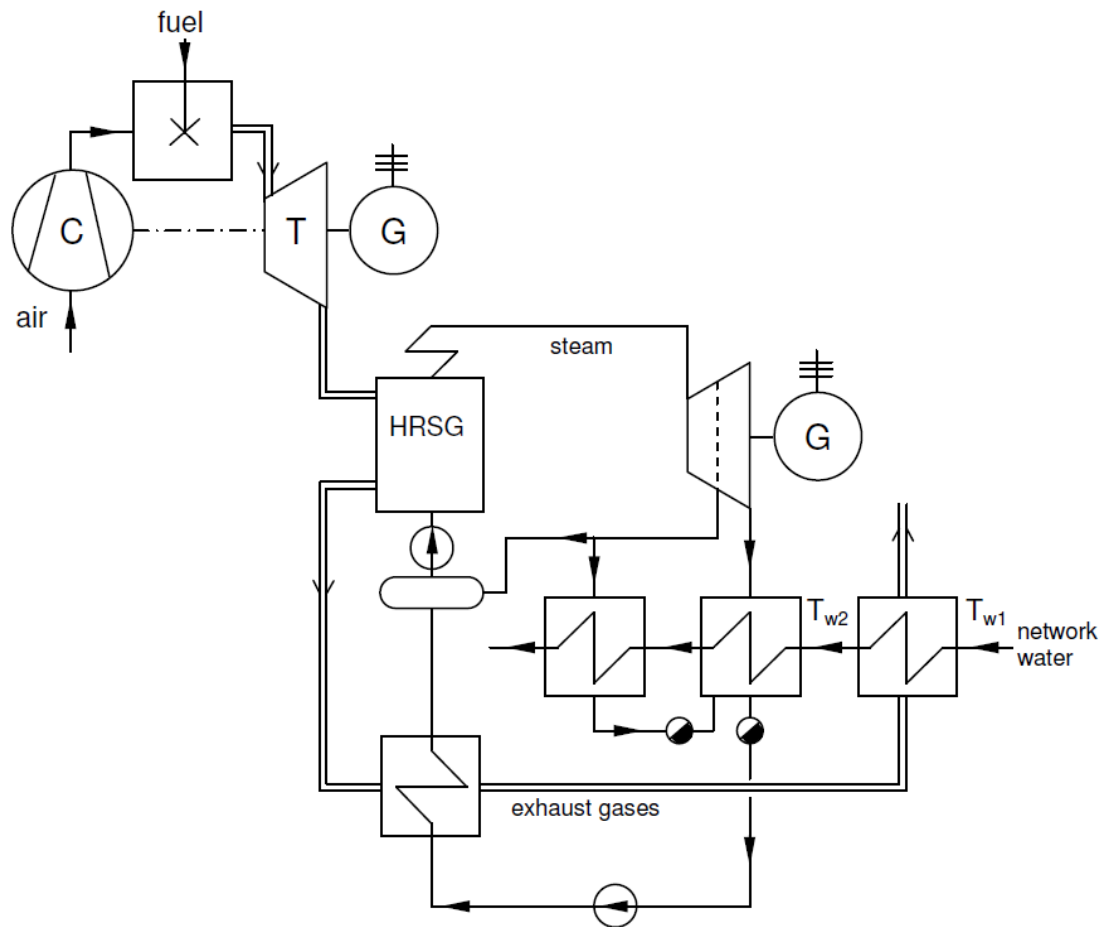


Fig. 5.22. Single-pressure gas and steam CHP unit; C - compressor; T - gas turbine, G - generator; T_{w1} , T_{w2} - temperature of network water; HRSG - heat recovery steam generator

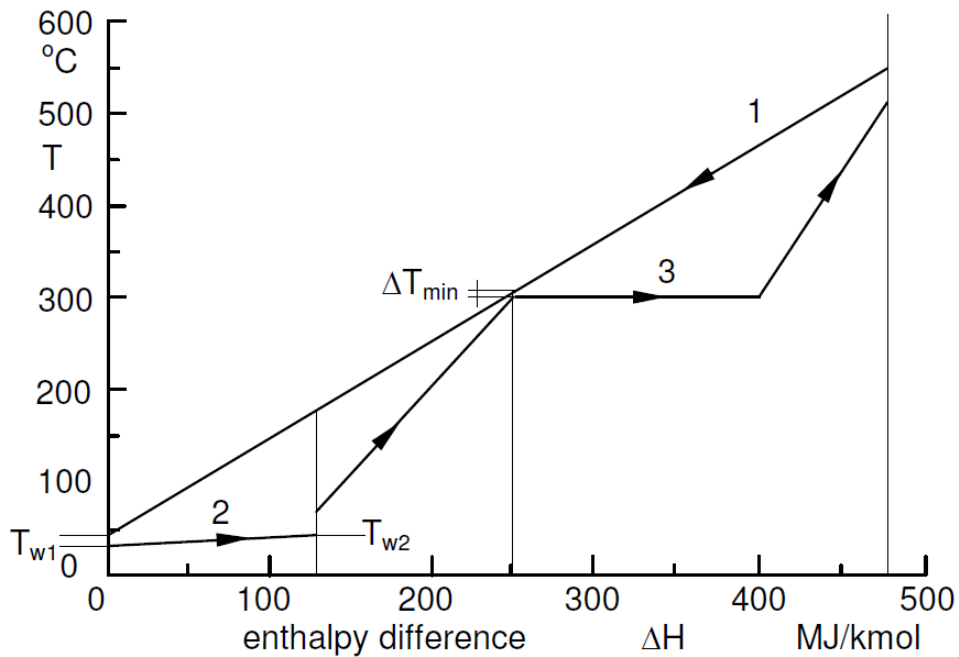


Fig. 5.23. Temperature distribution in the single-pressure heat recovery steam generator; 1 - combustion gases, 2 - network water, 3 - water in the steam cycle, $\Delta T_{\min}$ - pinch point temperature difference

Gas-and-steam systems combine the advantages of both separate gas and steam cycles eliminating their drawbacks [4, 8, 10]. The gas cycle (cycle of the gas turbine) displays the advantage that a much higher temperature of the working fluid can be applied thanks to direct heat transfer. A drawback of the gas cycle, however, is the high temperature of the flue gas at the outlet from the gas turbine. A drawback of the steam cycle are rather low parameters of the live steam. Due to material limitations in the steam cycle the considerable difference in temperature between combustion gas and the working fluid is not sufficiently utilised, the consequence of which are high exergy losses. An advantage of the system cycle is a low temperature of condensation (low isotherm of the thermodynamic cycle of the engine). The advantages of both cycles, connected with a simultaneous elimination of their drawbacks, mean that the energy efficiency of the combined gas and steam cycle amounts to 50 to 55 (60 per cent). The application of a gas-and-steam cycle is also ecologically beneficial because emissions of SO_2 , NO_x , CO_2 and dust are reduced. An additional advantageous effect is lower demand for industrial water and reduction in irreclaimable losses of water. The gas-and-steam cycle belongs to the group of cascade processes obtained by connecting the cycle of various

working media characterised by convenient properties in different ranges of temperature. Additional energy-ecological effects are achieved by applying gas-and-steam cycles in CHP plants. Gas-and-steam CHP plants fired with natural gas ensure higher savings in the chemical energy of fuels than those achieved in CHP plants fired with hard coal, due to the higher coefficient of cogeneration.

The following ways of joining the gas cycle with steam cycle, realised in practice, can be distinguished:

- series connection in which the input energy is supplied to the combustion chamber of the gas turbine, and the steam generator situated behind the outlet of the gas turbine plays the role of a heat recovery boiler,
- series-parallel connections in which the input energy is supplied to both the combustion chamber of the gas turbine and the steam generator, to which the flue gases from the outlet of the gas turbine are supplied containing a large amount of oxygen; this system is often called an after-burning system,
- parallel connections in which the steam cycle is fed from two independent units, viz., the steam boiler and the heat recovery boiler of the gas cycle; both these unit are joined only on the steam side.

Series connections are applied mainly in recently designed gas-and-steam systems. Such a connection is most useful from the thermodynamic point of view because the advantages of the gas cycle are fully utilised. The energy efficiency of the gas-and-steam cycle depends, first of all, on the temperature between the combustion gases and the temperature of water and steam in the heat recovery boiler. The application of double- or three-pressure steam cycles results in a decrease of exergy losses and an improvement in the thermodynamic performance of the cycle.

In the gas turbine system the excess air ratio in the combustion chamber is higher in order to reduce the temperature of flue gases before entering the gas turbine. This, however, lowers the efficiency of the gas turbine because the excess air is irreversibly compressed and then also irreversibly expanded (as a component of the flue gases), and this effect is accompanied by considerable losses of exergy. These losses may be reduced by injecting steam into the working medium before it is pressed into the gas turbine (so-called Cheng cycle) or by injecting water into the compressed air (humid air turbine - HAT). In the latter case it should be stressed that the compression of water requires much less input energy than the compression of air. HAT provides good conditions for the production of heat in cogeneration. The flue gases leaving the turbine are characterised by a temperature of about

120°C and contain much steam. Thanks to its condensation much heat can be obtained for preheating network water without considerable exergy losses.

The construction of small-scale CHP units at the place of the consumption of heat permits to reduce considerably the costs of heating networks and losses in transporting the heat. The construction of these CHP units are, however, expedient when:

- demand for heat is not too small,
- the CHP is automatised and easily handled,
- its operation is not strenuous for the consumers (due to noise, vibrations, the emission of flue gases etc.),
- the cost of fuels is not too high.

Small-scale CHP units are equipped with piston combustion engines or gas turbines. The former may be fed with liquid or gaseous fuels(e.g., natural gas or biogas). A single piston engine as a module of the CHP unit has a power rating of 70 to 300 kW and a heating flux of 130 to 550 kW. Development in the construction of small-scale gas turbines has made it possible to realise units below 70 kW (even of 30 kW).

The electrical efficiencies of a piston combustion engine and small-scale gas turbine are comparable (34÷37per cent). Also the energy efficiency of the whole CHP is in both cases similar. Better energy effects are achieved in gas-and-steam cycles if the heat recovery steam generator, fed with combustion gases from the piston engine or gas turbine, serves to produce steam for driving the steam turbine, cogenerating heat and electricity. In small-scale gas turbines more and more often regeneration of heat is included, i.e., the compressed air is preheated by means of flue gases, which distinctly improves the efficiency of the turbine although it lowers the temperature of the flue gases before entering the heat recovery steam generator.

The cogeneration of heat and electricity in small-scale CHP units can be conveniently realised by applying combustion piston engines. In this type of CHP units heat is received from the cooling system of the engine and the combustion gases leaving the engine. A CHP plant with combustion piston engine is usually constructed modularly. The respective modules can be thrown into and out of gear. This system is usually supplemented by a water heater.

The heat obtained from the cooling system of the engine and from the flux of combustion gases at the outlet of turbine may be expressed by the formula [10]:

$$\dot{Q}_u = \dot{P}LHV(\varepsilon_c + \varepsilon_{fg}\eta_{Esg}) \quad (5.66)$$

$\dot{Q}_u$ - useful heat flux,

$\dot{P}$ - consumption of fuel,

$\varepsilon_c, \varepsilon_{fg}$ - relative energy losses concerning cooling system and outlet of a gas turbine,

η_{Esg} - energy efficiency of heat recovery steam generator.

The electrical power is calculated as follows:

$$N_{el} = \dot{Q}_u \frac{\eta_{E pce}}{\varepsilon_c + \varepsilon_{fg} \eta_{E sg}} \quad (5.67)$$

where $\eta_{E pce}$ denotes electrical energy efficiency of combustion engine.

Savings in the cumulative energy of fuels in the case of gas and gas-and-steam CHP plants are calculated by means of the relation:

$$-\Delta E_{ch}^* = \frac{N_{el} \eta_{et}}{\eta_{E pp} \eta_{d pp}^* \eta_{et}'} + \frac{\dot{Q} \eta_{ht}}{\eta_{E hp} \eta_{d hp}^* \eta_{ht}'} - \frac{\dot{P} LHV}{\eta_{d CHP}^*} \quad (5.68)$$

where:

$-\Delta E_{ch}^*$ - savings in the cumulative energy of fuels achieved by cogeneration,

N_{el} - electric power produced in the CHP,

η_{et}, η_{et}' - efficiencies of the transformation and transmission of electricity from the CHP plant and the replaced power station,

$\eta_{E pp}$ - net energy efficiency of the replaced power plant,

$\eta_{d pp}^*, \eta_{d hp}^*, \eta_{d CHP}^*$ - cumulated energy efficiencies of delivering the fuel to the replaced power station, the heating and the gas-and-steam CHP plant,

$\dot{Q}$ - thermal power of the CHP plant,

η_{ht}, η_{ht}' - efficiency of transmitting heat from the CHP plant and the replaced heating plant to the consumers,

$\dot{P} LHV$ - consumption of the chemical energy of fuel in a gas or gas-and-steam CHP plants.

The choice of the replaced power station should depend on the ability of the CHP plant to produce electricity in the respective zones of the load of the national electro-energy system. The least effective case results from the assumption of replacing electricity produced in the basic zone. Then the efficiency of the replaced power station concerns the most modern power station.

5.5. Trigeneration – CHP plant integrated with a cooling system

5.5.1. Introduction

Similarly as in the case of centralised supply of heat, which has a long tradition, the centralised production and transmission of the cooling agents is possible. Cooling centres are usually applied in both industrial plants and in large complex buildings. The cooling agent can be produced by means of compressors or absorption cooling units. In the case of CHP plants integrated with cooling systems, the application of absorption coolers is of special interest.

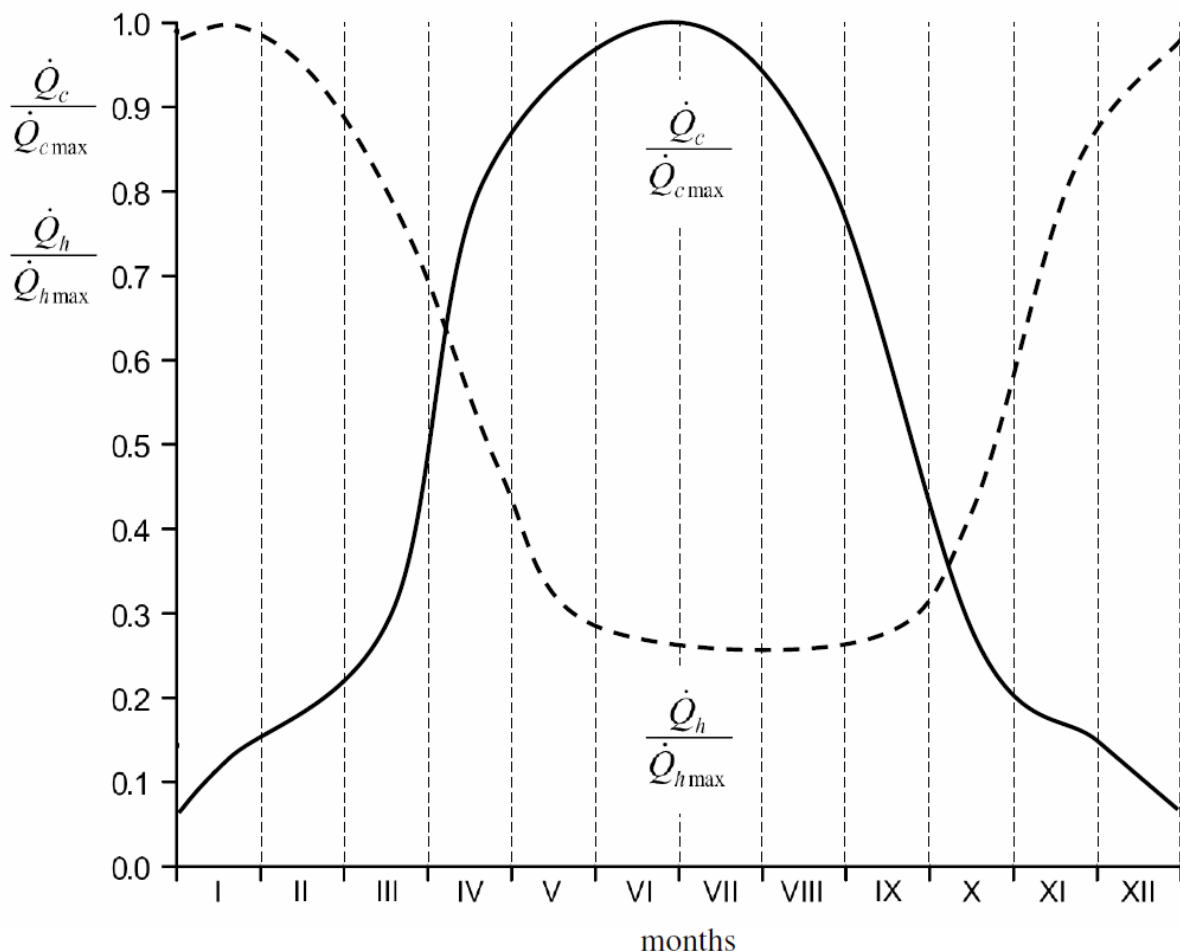


Fig.5.24. Exemplary annual diagram of heat and cooling agent demand adapted from Zahoransky [17]

Demands for heat and cooling agents mutually shift in the course of a year. Figure 5. 24 presents as an example the actual annual diagram of heat and a cooling agent demand

[17]. In summer the demand for a cooling agent is covered by systems with absorption coolers, influencing the energy and economic effects of CHP. Thus, so-called “trigeneration” systems come into play, that is heat and electricity cogeneration is integrated with the production of the cooling agent. Trigeneration systems can also be realised by applying compressor coolers or hybrid systems. Trigeneration systems applied in complex buildings are called BCHP (Buildings, Cooling, Heating and Power). The crucial elements in this technique are absorption coolers, which make it possible to utilise waste heat for the purpose of cooling.

5.5.2. Centralised production of cooling agent

As mentioned in the introduction to this section, similarly as in centralised heat production there are also systems of centralised production of the cooling agents. In the latter case the temperature of the feeding water amounts to $4\div 5^{\circ}\text{C}$ and the temperature of the returned water to $12\div 15^{\circ}\text{C}$. Generally the difference between the temperature of the feeding and returned water amounts to 9K, and the applied parameters are $4/13^{\circ}\text{C}$ [7].

In centralised cooling systems compressor or absorption coolers may be used. If the price of electricity is favourable (e.g., electricity from hydro-electric power stations) it is feasible to apply compressor coolers. When the structure of electricity production is dominated by thermal power plants, the application of absorption coolers provided with heat from CHP plants is energetically and economically more effective. There are also systems of centralised production of cooling agents fed by heat from heating plants or a source of waste heat. Where an absorption cooler is used with a CHP unit provided with gas and steam cycle, input energy carriers may be flue gases, heating steam or hot water.

In comparison with individual systems a centralised supply with cooling agents is more effective thanks to the improved efficiency of the production of the cooling agent, the lower costs of operation, and a smaller site. In choosing a centralised delivery of cooling agents, however, the location of the cooling centre must be taken into account, as well as the kind and cost of input energy and the possibility of applying differentiated tariffs for electricity.

The effectiveness of centralised cooling systems can be increased by applying cooling stores, which permit the operation of cooling installations to be adapted to partial loading, a reduction in the capital cost thanks to a lower power rating of the cooler, and also a reduction

$$\begin{aligned}
-\Delta E_{cht} = & Q_{ho} \left[\frac{1}{\eta_{Ehp} \eta'_{ht}} - \frac{1}{\eta_{EHP} \eta_{ht} (1 - \varepsilon_h)} \right] + \frac{Q_{co}}{COP_a} \left[\frac{1}{\eta_{Ehp} \eta'_{ct}} - \frac{1}{\eta_{EHP} \eta_{ct} (1 - \varepsilon_c)} \right] + \\
& + E_{elo} \left[\frac{1}{\eta_{Epp} \eta'_{et}} - \frac{1}{\eta_{EHP} \eta_{et} (1 - \varepsilon_{el})} \right]
\end{aligned} \tag{5.69}$$

where:

$-\Delta E_{cht}$ - saving of the chemical energy of fuel in the case of trigeneration,

Q_{ho} - heat demand loco consumer,

Q_{co} - cooling agent demand loco consumer,

E_{elo} - electricity demand loco consumer,

η_{Ehp} - net energy efficiency of the heating plant,

η_{EHP} - gross energy efficiency of the CHP plant,

η_{ht}, η'_{ht} - efficiency of heat transmission from CHP and heating plant, respectively,

η_{Epp} - net energy efficiency of the power plant,

η_{ct}, η'_{ct} - efficiency of transmission of the cooling agent from the trigeneration system and from separate installation,

COP_a - coefficient of performance of the absorption chiller,

ε_h - coefficient of own heat consumption,

ε_c - coefficient of own cooling agent consumption,

ε_{el} - coefficient of own electricity consumption in the CHP.

In relation (5.69) it is assumed that the demand for heat, cooling agent and electricity is the same in the trigeneration system as it is in the separate production of the aforementioned energy carriers. The consumption of electricity in the absorption cooler has been neglected because it is inconsiderable.

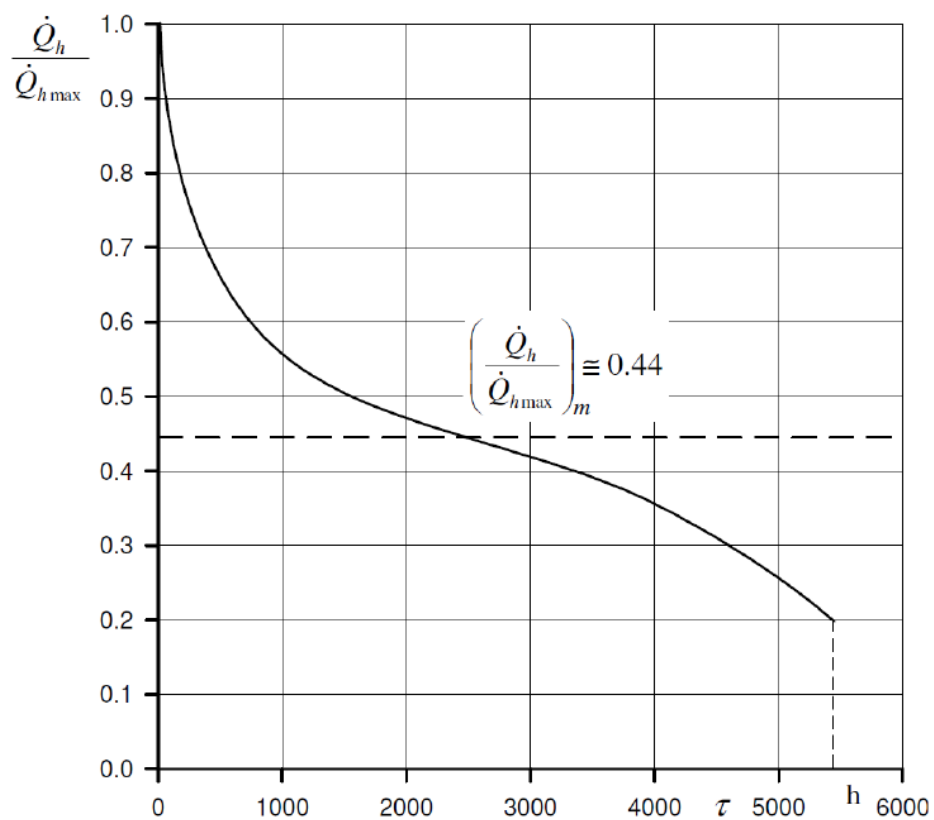


Fig.5.26. Duration curve of heat demand

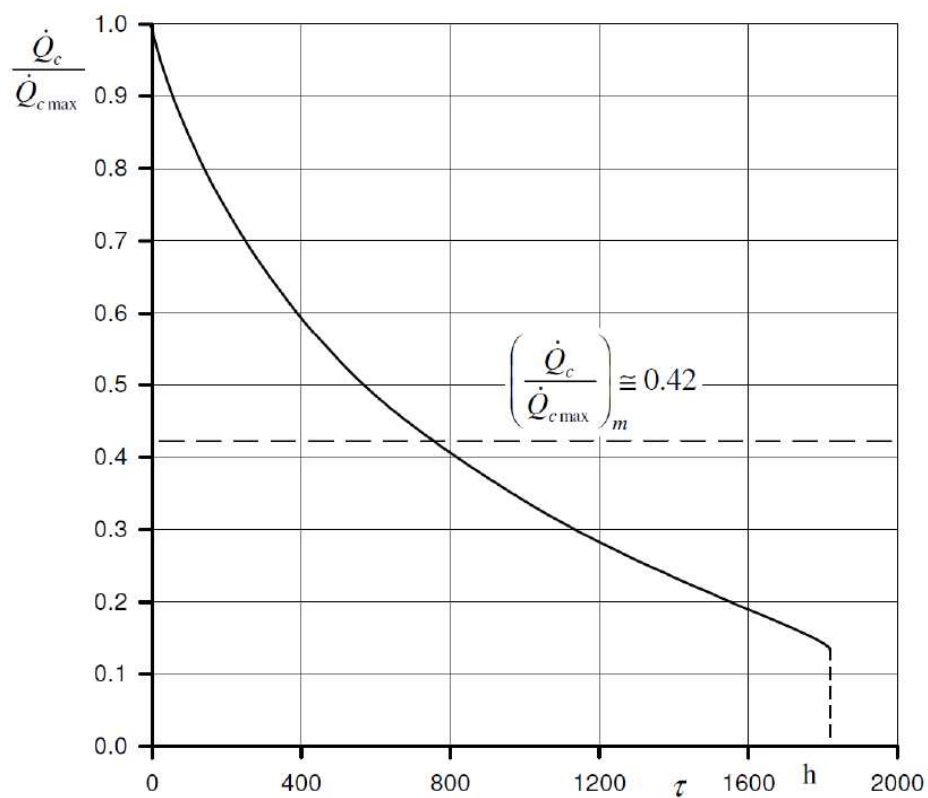


Fig.5.27. Duration curve of cooling agent demand

Figure 5.26 and 5.27 present reduced duration curves of heat in the heating season and of the cooling agent in summer. The duration of heating is assumed to be $\tau_h = 5400h$, and the duration of the demand for the cooling agent $\tau_c = 1800h$ [7].

The annual demand for heat and cooling agents by consumers is expressed by the relations:

$$Q_{ho} \cong 0,44 \dot{Q}_{h \max o} \tau_h \quad (5.70)$$

$$Q_{co} \cong 0,42 \dot{Q}_{c \max o} \tau_c \quad (5.71)$$

where:

Q_{ho} - annual demand for heat,

$\dot{Q}_{h \max o}$ - maximum flux of heat loco consumer,

τ_h - duration of the heating season,

Q_{co} - annual demand for cooling agent,

$\dot{Q}_{c \max o}$ - maximum flux of the cooling agent loco consumer,

τ_c - duration of the demand for the cooling agent.

The ratio of the demand for cooling agents to the demand for heat may be expressed as:

$$\frac{Q_{co}}{Q_{ho}} \cong \frac{1}{3} \frac{\dot{Q}_{c \max o}}{\dot{Q}_{h \max o}} \quad (5.72)$$

Denoting the ratio Q_{co} / Q_{ho} by α , the relation between the gross production of the cooling agent and heat results from the equation:

$$Q_c = \alpha \frac{\eta_{ht}(1-\varepsilon_h)}{\eta_{ct}(1-\varepsilon_c)} Q_h \quad (5.73)$$

The relation between the production of heat and the cooling agent and the production of electricity is:

$$E_{el} = \sigma \left(Q_h + \frac{Q_c}{COP_a} \right) \quad (5.74)$$

where σ denotes the factor of cogeneration.

Making use of Eqs.(5.72), (5.73), (5.74) in Eq.(5.69), and assuming that, $\eta_{et} \cong \eta'_{et}$; $\eta_{ht} \cong \eta'_{ht}$; $\eta_{ct} \cong \eta'_{ct}$; $(1-\varepsilon_h) \cong (1-\varepsilon_c)$ we get [20]:

$$\left(-\frac{\Delta E_{ch}}{Q_h}\right)_t = \left(1 + \frac{\alpha}{COP_a}\right) \left[\sigma \left(\frac{1 - \varepsilon_{el}}{\eta_{E\ pp}} - \frac{1}{\eta_{E\ CHP}} \right) + \frac{1 - \varepsilon_h}{\eta_{E\ hp}} - \frac{1}{\eta_{E\ CHP}} \right] \quad (5.75)$$

The effect of trigeneration is assessed quantitatively by the coefficient of the increase of cogeneration effects [20]:

$$\beta = \frac{\left(-\frac{\Delta E_{ch}}{Q_h}\right)_t}{-\frac{\Delta E_{ch}}{Q_h}} \quad (5.76)$$

Comparing (5.40) with (5.75) and applying (5.72) as well assuming that $\eta_{ht} = \eta_{ct}$, we get:

$$\beta \cong 1 + \frac{\chi}{3COP_a} \quad (5.77)$$

$$\chi = \frac{\dot{Q}_{c\ max\ o}}{\dot{Q}_{h\ max\ o}} \quad (5.78)$$

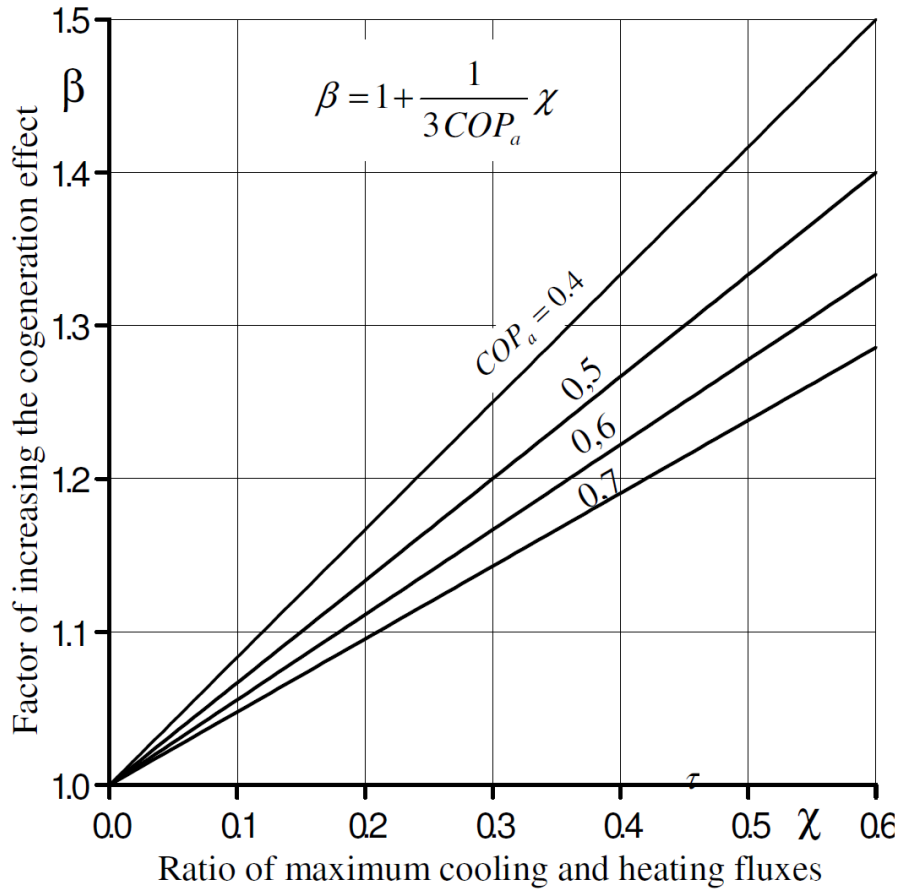


Fig.5.28. Factor of increasing the cogeneration effect thanks to trigeneration

The effect of increased savings in the chemical energy of fuel in the cogeneration system due to trigeneration is illustrated in Figure 5.28 [20]. The results presented there must be interpreted as quantities calculated in comparison with separate production of heat, electricity and cooling agent. This means that in the case of the given absorption cooler the effect of cogeneration grows with the increasing demand for the cooling agent. The growing values of the coefficient β with the decreasing the COP_a (coefficient of performance) of the cooler should not be interpreted as meaning that a worse COP_a is better, because the consumption of input energy in the cooler increases. We may only speak of less severe consequences of the worse COP_a of the absorption cooler if it is integrated with a CHP plant. Thus, a CHP partially compensates the worse COP_a of the absorption chiller.

5.6. Analysis of the index of primary energy savings concerning cogeneration

The Directive 2004/8/EC [1, 2], a part of which has been quoted in the Appendix E to this book, includes the index PES (Primary Energy Savings), which determines relative savings in the chemical energy of fuels achieved thanks to cogeneration. The equation (E2) in Appendix E defines the index PES. The term “reference energy efficiency” complies with the term “energy efficiency of a replaced process,” up to now used in literature [11,12].

Substituting in Eq. (E1) terms expressing arithmetical partial efficiencies concerning the production of heat and electricity in cogeneration, viz. [19]:

$$CHP\ H\eta = \frac{Q_{cog}}{E_{ch\ cog}} \quad (5.79)$$

$$CHP\ E\eta = \frac{E_{el\ cog}}{E_{ch\ cog}} \quad (5.80)$$

we get

$$PES = 1 - \frac{E_{ch\ cog}}{E_{ch\ hp} + E_{ch\ pp}} = \frac{-\Delta E_{ch}}{E_{ch\ sep}} \quad (5.81)$$

where:

Q_{cog} , $E_{el\ cog}$ - production of heat and electricity in the CHP,

$E_{ch\ cog}$ - consumption of the chemical energy of fuels in the CHP,

$E_{ch\ hp}$, $E_{ch\ pp}$ - consumption of the chemical energy of fuels in a reference heating plant (replaced process) and reference power station (replaced process),

$-\Delta E_{ch}$ - savings of the chemical energy of fuels, $-E_{ch\ sep}$ consumption of the chemical energy of fuels concerning separate production of heat and electricity

Figure 5.11 presents a diagram of a CHP plant with a back-pressure turbine fired with coal. The consumption of the chemical energy of fuels in this CHP plant and in the separate production of heat and electricity is expressed by the following equations:

$$E_{ch\ cog} = \frac{(1+\sigma)Q_{cog}}{\eta_{E\ CHP}}; \quad (5.82)$$

$$E_{ch\ sep} = Q_{cog} \left(\frac{1}{\eta_{ref\ hp}} + \frac{\sigma}{\eta_{ref\ pp}} \right) \quad (5.83)$$

Substituting (5.82) and (5.83) in (5.81) we get:

$$PES = 1 - \frac{1+\sigma}{\eta_{E\ cog} \left(\frac{1}{\eta_{ref\ hp}} + \frac{\sigma}{\eta_{ref\ pp}} \right)} \quad (5.84)$$

Figure 5.30 presents the index PES in the considered case, which shows that the condition $PES \geq 10\%$ might be safely satisfied by CHP plants with an efficiency exceeding 75% and a factor of cogeneration higher than 0.3.

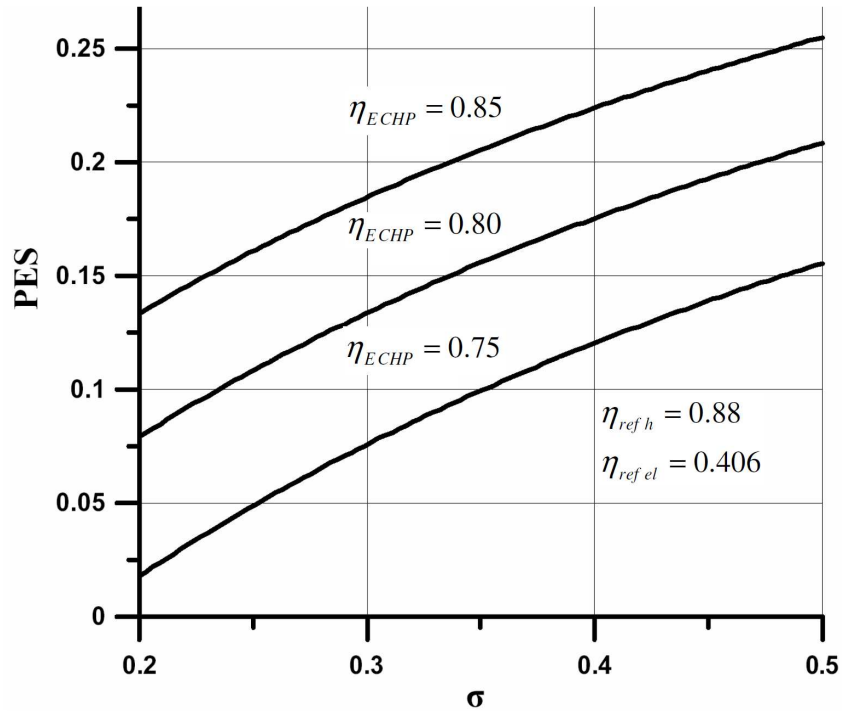


Fig. 5.29. Index PES in the case of a back-pressure turbine

Figure 5.18 presents a diagram of a power plant adapted for the production of heat. In this adaptation it is assumed that the consumption of the chemical energy of fuels E_{ch} does not undergo any changes, viz.:

$$E_{ch} = \frac{E_{el}}{\eta_{E\ pp}} = const \quad (5.85)$$

The consumption of the chemical energy of fuels $E_{ch\ cog}$, burdening the production in cogeneration, results from the relation:

$$E_{ch\ cog} = E_{ch} - E_{ch\ c} \quad (5.86)$$

where

$$E_{ch\ c} = \frac{E_{el\ c}}{\eta_{E\ pp}} \quad (5.87)$$

where

$E_{el\ c}$ - production of electricity in the condensation mode after the adaptation of the power plant,

$\eta_{E\ pp}$ - energy efficiency of the production of electricity in the condensation mode.

The amount of electricity produced in the condensation mode after the adaptation of the power plant is calculated taking into account the index of power loss and the factor of cogeneration:

$$E_{el\ c} = E_{el} - uQ_{cog} - \sigma Q_{cog} \quad (5.88)$$

where the coefficient of power decrease is expressed by:

$$u = \frac{-\Delta N_{el}}{\dot{Q}_{cog}} \quad (5.89)$$

where

$-\Delta N_{el}$ - power decrease due to adaptation,

$\dot{Q}_{cog}$ - flux of heat provided by the adapted power plant.

Introducing (5.85), (5.87), (5.88) in (5.86) we get:

$$E_{ch\ cog} = \frac{(u + \sigma)Q_{cog}}{\eta_{E\ pp}} \quad (5.90)$$

Hence:

$$PES = 1 - \frac{\sigma + u}{\eta_{E\ pp} \left(\frac{1}{\eta_{ref\ hp}} + \frac{\sigma}{\eta_{ref\ pp}} \right)} \quad (5.91)$$

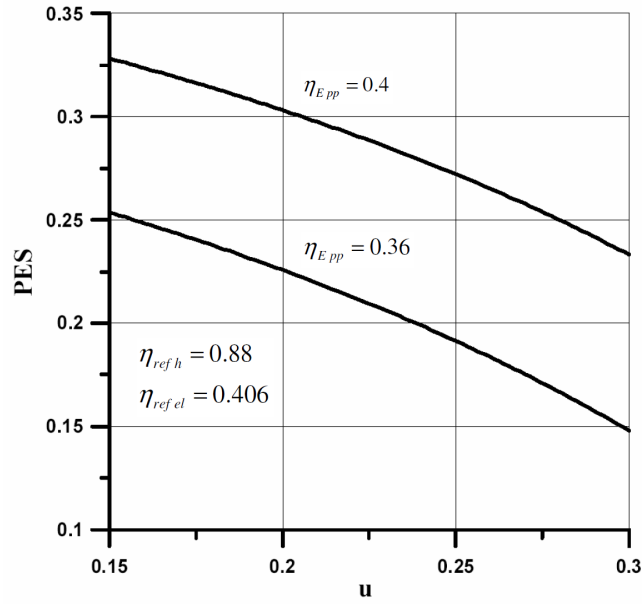


Fig. 5.30. Index PES concerning the power plant adapted for heat production

Figure 5.30 presents the index PES concerning the adapted power plant for heat production. The index PES depends strongly on the coefficient of power decrease. Consuming steam for heating purposes from the receiver between the medium- and low-pressure part of the turbine ($u \cong 0.2$), the index PES exceeds 0.2. The consumption of steam from the outlet of high-pressure part of the turbine ($u \cong 0.4$), however, leads to a drop in the index PES to less than 10%.

Figure 5.31 presents the diagram of a gas-and-steam CHP plant fired with natural gas.

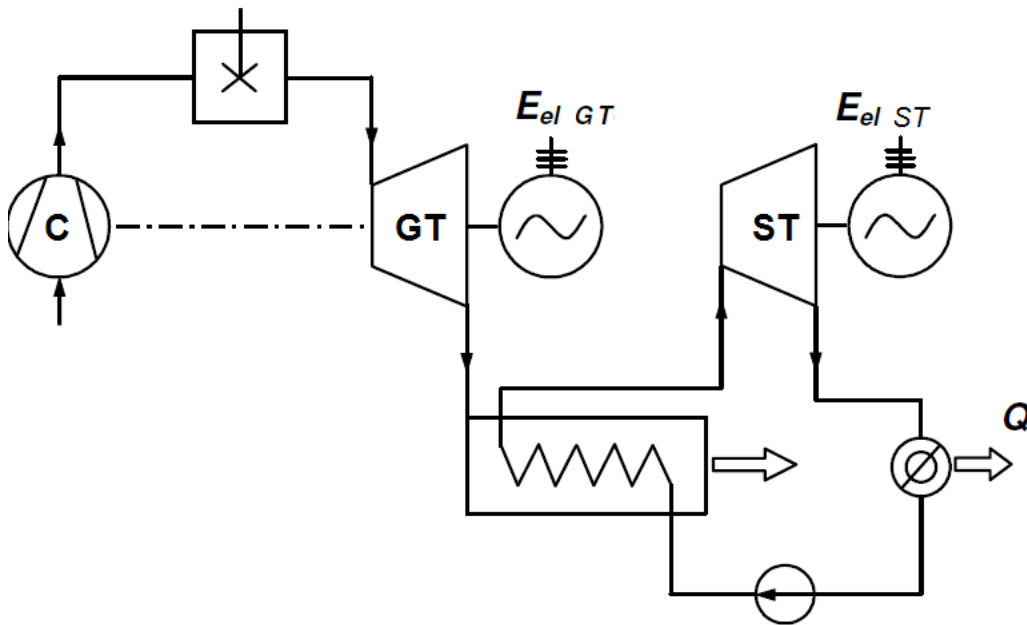


Fig. 5.31. Diagram of a gas-and-steam CHP plant; C - compressor, GT - gas turbine, ST - steam turbine

The index PES is calculated based on the relation (5.81). The consumption of the chemical energy of fuels is calculated based on the energy efficiency of the gas-and-steam CHP plant.

$$E_{ch\ cog} = \frac{Q_{cog} + E_{el\ cog}}{\eta_{E\ CHP\ gs}} \quad (5.92)$$

The amount of electricity produced in cogeneration is calculated as follows:

$$E_{el\ cog} = \sigma Q_{cog} \quad (5.93)$$

Hence:

$$PES = 1 - \frac{1 + \sigma}{\eta_{E\ CHP\ gs} \left(\frac{1}{\eta_{ref\ hp}} + \frac{\sigma}{\eta_{ref\ pp}} \right)} \quad (5.94)$$

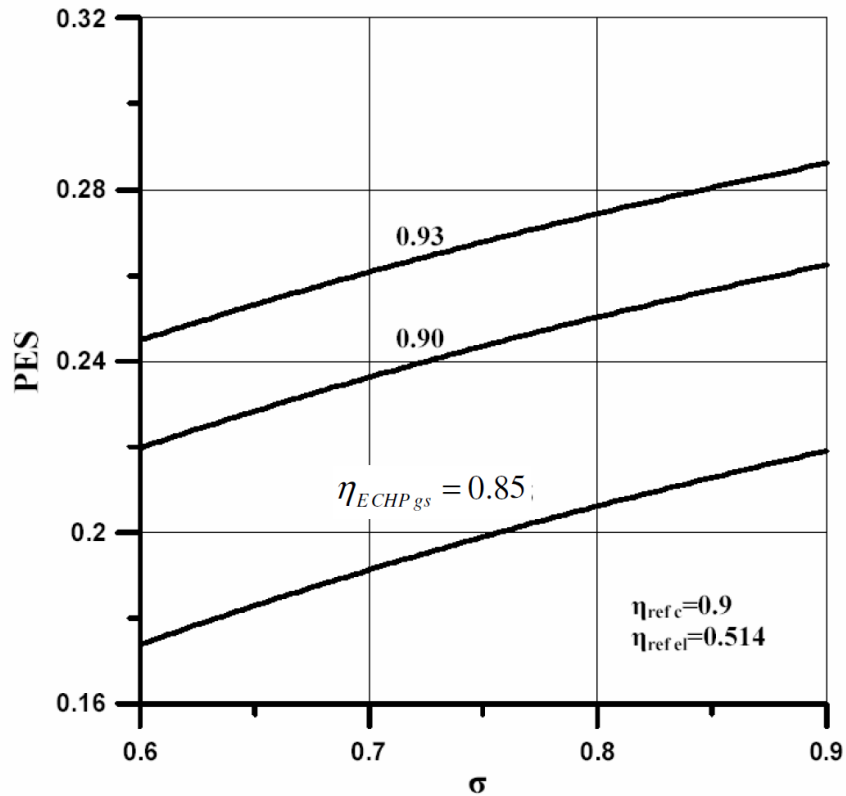


Fig. 5.32. Index PES concerning a gas-and-steam CHP plant

Figure 5.33 presents the index PES, which indicates a high effectivity in the realisation of the gas-and-steam CHP plant. In the case of modern gas-and-steam CHP plants the index PES takes the mean value of about 25per cent.

Figure 5.34 presents a small-scale CHP plant equipped with a piston gas engine.

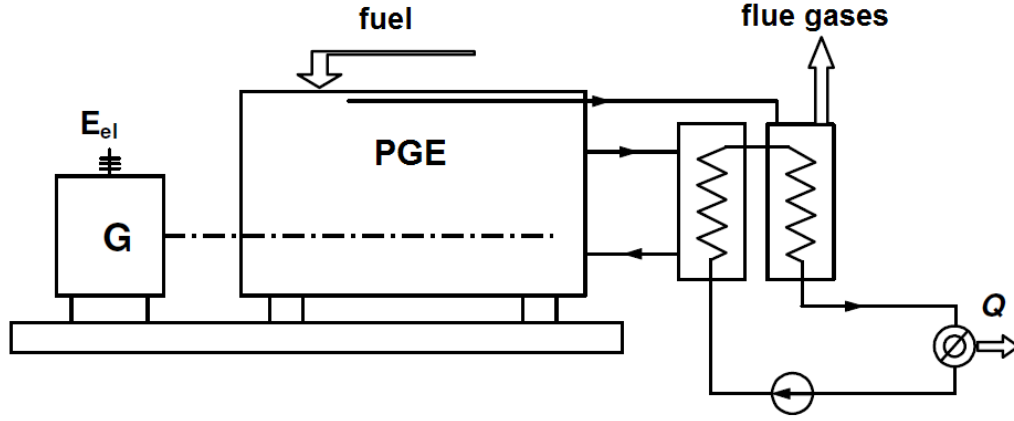


Fig. 5.33. Diagram of a small-scale CHP plant equipped with a piston gas engine; PGE - piston gas engine; G - generator

In the derivation of the formula describing the index PES it was taken into account that the efficiency of transmitting heat and electricity is more favourable in a small-scale CHP plant than in their separate production and transmission.

For this purpose the ratio of the efficiency of the transmission of electricity and heat produced separately to that of transmitting them in a small-scale CHP plant has been quoted:

$$\frac{\eta'_{et}}{\eta_{et}} = \beta_1 \quad \frac{\eta'_{ht}}{\eta_{ht}} = \beta_2 \quad (5.95)$$

where:

η'_{et}, η'_{ht} - efficiency of transmission concerning electricity and heat produced separately,

η_{et}, η_{ht} - efficiency of transmission concerning electricity and heat produced in a small-scale CHP plant.

The relation concerning PES takes the following form:

$$PES = 1 - \frac{1 + \sigma}{\eta_{E \text{ CHP } g \text{ G}} \left(\frac{1}{\eta_{ref \text{ hp}} \beta_2} + \frac{\sigma}{\eta_{ref \text{ pp}} \beta_1} \right)} \quad (5.96)$$

where $\eta_{E \text{ CHP } g \text{ G}}$ denotes the gross efficiency of a small-scale CHP plant equipped with a piston gas engine.

As reference values and ratios β_1 and β_2 the following values have been assumed:

$$\eta_{ref\ pp}=0,39; \eta_{ref\ hp}=0,9; \beta_1=\beta_2=0,95$$

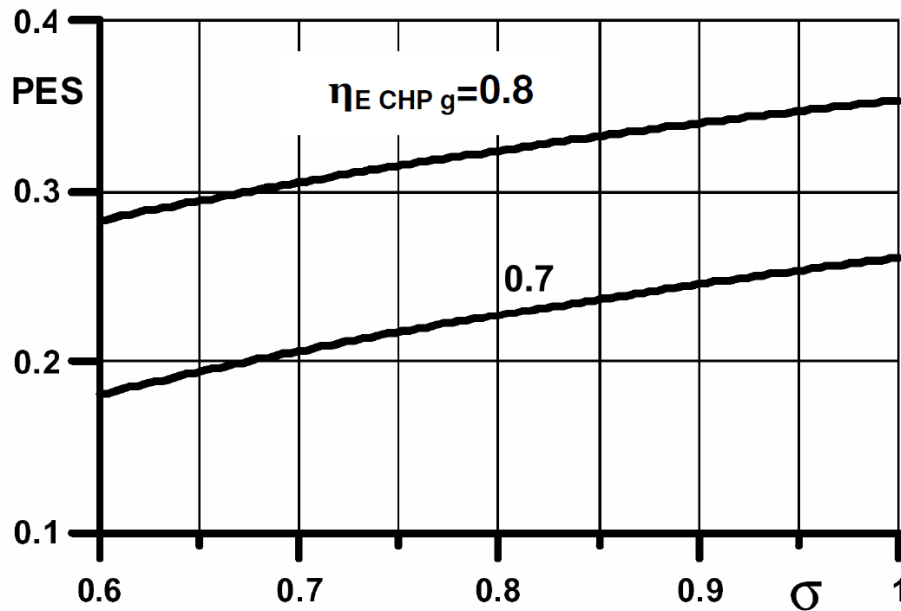


Fig.5.35 Index PES concerning a small-scale CHP plant equipped with a piston gas engine

The results presented in Figure 5.35 indicate that the realisation of distributed cogeneration systems based on piston gas engines ensures the attainment of high values of the index PES.

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Chapter 6

SYSTEMS APPROACH TO ENERGY-ECOLOGICAL ANALYSIS OF COMPLEX BUILDINGS

The mathematical model of the balance of direct energy consumption of energy carriers in complex buildings is based on Leontief's „input-output analysis" [7]. Energy carriers are divided into those produced inside complex buildings, and possibly supplemented from outside, and energy carriers entirely supplied from outside. Direct consumption of energy carriers does not, however, comprise all the energy required for the needs of complex buildings, because the fuels, materials and energy carriers, supplied to them, are burdened by energy consumption due to:

- the extraction of primary energy and raw materials,
- the processing of primary energy to final energy carriers,
- the transport and consumption of devices for gaining and processing energy carriers.

The balance of cumulative energy consumption is also expressed by the “input-output analysis”, assuming that connections between complex buildings and the entire economy of a country are weak. This means that in the balance of cumulative energy consumption in complex buildings the indices of cumulative energy consumption concerning the input data (e.g., fuels and water) are assumed to be quantities known a priori, equal to the average values for the whole country. The mathematical model of the balance of cumulative emissions of complex buildings may be formulated based on analogical assumptions. A complete thermo-ecological analysis should also include the depletion of non-renewable energy resources. This may be expressed by the so-called thermo-ecological cost, based on the balance of cumulative exergy consumption. The thermo-ecological cost expresses the cumulative exergy consumption of non-renewable natural resources, including their additional consumption due to the necessity of compensating the environmental losses caused by the release of harmful emissions connected with the existence of complex buildings. Balances of the thermoecological costs of complex buildings are also based on input-output analysis, taking into account the principle of weak connections. A systems approach, also based on input-output analysis may be applied for the assessment of the system effects of the rationalisation of energy management in complex buildings. The input values in this analysis are the results of thermodynamic process analysis concerning the individual consumers of energy carriers or the process of producing energy carriers.

6.1 Mathematical model of the balance of direct energy consumption in complex buildings

Energy management in complex buildings consists of two basic subsystems: the energy subsystem (production of energy carriers) and the subsystem of consumers. The energy subsystem serves for the production, conversion, transmission and distribution of energy carriers consumed in the subsystem of consumers. Energy carriers assigned to the needs of the subsystem of consumers are produced in a network of mutually connected energy processes. A particular complexity of interconnections characterises the management of power, heating and cooling (as BCHP systems applied in buildings). Some part of these interconnections has a feedback character, which complicates energy balances by applying separate balances for each energy carrier. The arduous approximative method of separate balances can be avoided by making use of a mathematical model of the energy balance of complex buildings [15]. The

mathematical model of complex buildings is a set of equations resulting from the balance of all energy carriers [1, 2, 3, 4, 6].

The assumptions of the mathematical model of the energy balance of complex buildings are based on input-output analysis (input-output economics) [7] with supplement characteristics industrial energy management [14]. In some energy branches energy carriers are produced in peak and basic installations. In such a case the peak and basic part of the production of energy carriers are to be distinguished. Also the main and by-production of energy carriers should be taken into account. In some cases the internal production of energy carriers is supplemented by supplies from outside (e.g., electricity when a CHP unit is installed in a complex buildings). The activity of energy management of complex buildings is possible thanks to energy carriers supplied from outside (mainly fuels).

The flow of energy carriers from the energy subsystem to the subsystem of consumers can be presented in the form of an interbranch table (Table 6.1). Similar to Leontief's input-output analysis [7], the structure of this table is based on the following principles:

- the energy subsystem is divided into production branches; to each branch corresponds one energy carrier,
- the energy carrier may be the main product of the given branch or a by-product of some other branch, or be supplied from outside,
- the energy carriers supplied from outside may supplement the internal production or may be energy carriers entirely supplied from outside,
- the energy carriers are consumed completely inside the balance cover shield of complex buildings, mainly for the needs of the subsystem of consumers and partly for the internal requirements of the energy subsystem.

The mathematical model of complex buildings comprises a network of interdependences which exist in a real complex buildings between the subsystem of consumers and the energy subsystem, as well as inner relations between the energy processes. A general principle of the mathematical model is the assumption concerning a linear dependence between the production and consumption of energy carriers. In complex buildings the rate of production by the energy subsystem depends on the demand for energy carriers in the subsystem of consumers (for example, the users' needs for heat, hot tap water, etc.), and the internal needs resulting from connections between the energy branches [15].

The energy branch in complex buildings is defined as a group of devices and equipment in the energy subsystem which produces specific energy carriers, for example, the central heating system, cooling system and ventilation system. The consumer branch is defined as a group of rooms, devices and equipment in the subsystem of consumers, which consumes energy from the energy subsystem, for example, offices and auxiliary rooms.

Table 6.1 presents the structure of interbranch flows in complex buildings. There are two groups of energy carriers:

- energy carriers produced in the energy subsystem of complex buildings, possibly supplemented by external supplies (e.g., electricity),
- energy carriers supplied to complex buildings entirely from outside (mainly fuels).

Table 6.1. Input-output table of interbranch flows of energy carriers in complex buildings

Energy carrier	Input part					Output part	
	Main production		By-production		External supply	Interbranch flows	
	Peak part	Basic part	Energy subsystem	Subsystem of consumers		Energy subsystem	Subsystem of consumers

1	G_1	P_1	$\sum_{j=1}^n U_{1j}$	$\sum_{k=1}^p \bar{U}_{1k}$	D_{G1}	$\sum_{j=1}^n Z_{1j}$	$\sum_{k=1}^p \bar{Z}_{1k}$
...	...	...	...	...	...	...	...
i	G_i	P_i	$\sum_{j=1}^n U_{ij}$	$\sum_{k=1}^p \bar{U}_{ik}$	D_{Gi}	$\sum_{j=1}^n Z_{ij}$	$\sum_{k=1}^p \bar{Z}_{ik}$
...	...	...	...	...	...	...	...
n	G_n	P_n	$\sum_{j=1}^n U_{nj}$	$\sum_{k=1}^p \bar{U}_{nk}$	D_{Gn}	$\sum_{j=1}^n Z_{nj}$	$\sum_{k=1}^p \bar{Z}_{nk}$
$n+1$	0	0	0	0	D_{Dn+1}	$\sum_{j=1}^n Z_{n+1j}^D$	$\sum_{k=1}^p \bar{Z}_{n+1k}^D$
...	...	...	...	...	...	...	...
l	0	0	0	0	D_{Dl}	$\sum_{j=1}^n Z_{lj}^D$	$\sum_{k=1}^p \bar{Z}_{lk}^D$
...	...	...	...	...	...	...	...
m	0	0	0	0	D_{Dm}	$\sum_{j=1}^n Z_{mj}^D$	$\sum_{k=1}^p \bar{Z}_{mk}^D$

All balance equations concerning energy carriers gathered in the input-output table (Table 6.1) are formulated on the basis of the energy flow chart of the analysed building. According to the assumption concerning a linear relation between the production and consumption of energy carriers in complex buildings, the consumption of the i -th energy carrier in the j -th energy branch Z_{ij} and the k -th branch of consumers $\bar{Z}_{ik}$ can be expressed as follows:

$$Z_{ij} = a_{ij}^G G_j + a_{ij}^P P_j \quad (6.1)$$

$$Z_{lj}^D = a_{lj}^{GD} G_j + a_{lj}^{PD} P_j \quad (6.2)$$

$$\bar{Z}_{ik} = \bar{a}_{ik} \bar{G}_k \quad (6.3)$$

$$\bar{Z}_{lk}^D = \bar{a}_{lk}^D \bar{G}_k \quad (6.4)$$

where:

- $G_j, P_j, \bar{G}_k$ – main production (peak and basic part) of the i -th energy branch and k -th branch of consumers,
- Z_{ij} – consumption of the i -th energy carrier in the j -th branch of energy subsystem,
- D_{Gi} – external supplementary supply of the i -th energy carrier,
- D_{Dl} – the amount of the l -th energy carrier supplied entirely from outside,
- a_{ij}^G – coefficient of direct consumption of the i -th energy carrier per unit production of the j -th energy branch (peak part of production),
- a_{ij}^P – coefficient of direct consumption of the i -th energy carrier per unit production of the j -th energy branch (basic part of production),
- $\bar{Z}_{ik}$ – consumption of the i -th energy carrier in the k -th branch of the subsystem of consumers,
- $\bar{a}_{ik}$ – coefficient of direct consumption of the i -th energy carrier per unit production of the k -th branch of the subsystem of consumers,

- Z_{lj}^D – consumption of the l-th energy carrier supplied entirely from outside per unit production of the j-th energy branch,
- a_{lj}^{GD} – coefficient of direct consumption of the l-th energy carrier supplied entirely from outside in the j-th energy branch (peak part of production),
- a_{lj}^{PD} – coefficient of direct consumption of the l-th energy carrier supplied entirely from outside in the j-th energy branch (basic part of production),
- $\bar{Z}_{lk}^D$ – consumption of the l-th energy carrier supplied entirely from outside in the k-th branch of the subsystem of consumers.
- $\bar{a}_{lk}^D$ – coefficient of consumption of the l-th energy carrier supplied entirely from outside in the k-th branch of the subsystem of consumers.

$i, j = 1, 2, \dots, n$

$l = n+1, \dots, m$

$k = 1, 2, \dots, p$

n - number of the branch of energy carriers produced in the energy subsystem of complex buildings,

m - number of energy carriers entirely supplied from outside,

p - number of branches of consumers.

Also as in the case of by-production we can write:

$$U_{ij} = f_{ij}^G G_j + f_{ij}^P P_j \quad (6.5)$$

$$\bar{U}_{ik} = \bar{f}_{ik} \bar{G}_k \quad (6.6)$$

where:

- U_{ij} – by-production of the i-th energy carrier in the j-th energy branch of energy subsystem,
- f_{ij}^G – coefficient of by-production of the i-th energy carrier per unit production of the j-th energy branch (peak part of production),
- f_{ij}^P – coefficient of by-production of the i-th energy carrier per unit production of the j-th energy branch (basic part of production),
- $\bar{U}_{ik}$ – by-production of the i-th energy carrier in the k-th energy branch of subsystem of consumers,
- $\bar{f}_{ik}$ – coefficient of by-production of the i-th energy carrier per unit production of the k-th energy branch of subsystem of consumers.

When the consumption of energy carriers in the branch of subsystem of consumers is a quantity independent from their production (services such as garages), or if we have to do with office rooms or similar structures, then:

$$\bar{Z}_{ik} = C_{ik} \quad (6.7)$$

$$\bar{Z}_{lk}^D = C_{lk}^D \quad (6.8)$$

$$\bar{U}_{ik} = B_{ik} \quad (6.9)$$

where:

- C_{ik} – consumption of the i-th energy carrier from energy subsystem in the k-th branch of subsystem of consumers,
- C_{lk}^D – consumption of the l-th energy carrier supplied entirely from outside in the k-th branch of subsystem of consumers,
- B_{ik} – by-production of the i-th energy carrier in the k-th branch of subsystem of consumers.

Practically, the relations (6.7) to (6.9) are rather obvious in the case of complex buildings. The notations (6.3), (6.4) and (6.6) are in their general character close to the classical notation in Leontief's input-output analysis [7]. Further on the notations (6.7) to (6.9) are used.

The set of balance equations of energy carriers produced in the energy subsystem is expressed as:

$$\bigwedge_{i=1}^n: G_i + P_i + \sum_{j=1}^n f_{ij}^G G_j + \sum_{j=1}^n f_{ij}^P P_j + \sum_{k=1}^p B_{ik} + D_{Gi} = \sum_{j=1}^n a_{ij}^G G_j + \sum_{j=1}^n a_{ij}^P P_j + \sum_{k=1}^p C_{ik} \quad (6.10)$$

Similarly, the set of balance equations of energy carriers supplied entirely from outside is expressed as:

$$\bigwedge_{l=n+1}^m: D_{Dl} = \sum_{j=1}^n a_{lj}^{GD} G_j + \sum_{j=1}^n a_{lj}^{PD} P_j + \sum_{k=1}^p C_{lk}^D \quad (6.11)$$

In matrix notation the set of balance equations (6.10) concerning energy carriers produced in the energy subsystem takes the following form:

$$\mathbf{G} + \mathbf{P} + \mathbf{F}_G \mathbf{G} + \mathbf{F}_P \mathbf{P} + \mathbf{B} \mathbf{I}_v + \mathbf{D}_G = \mathbf{A}_G \mathbf{G} + \mathbf{A}_P \mathbf{P} + \mathbf{C} \mathbf{I}_v \quad (6.12)$$

where:

- $\mathbf{G}, \mathbf{P}$ – vectors of the main production of energy carriers concerning peak and basic part, respectively,
- $\mathbf{F}_G, \mathbf{F}_P$ – matrices of the by-production of energy carriers concerning peak and basic part of main production, respectively,
- $\mathbf{B}$ – matrix of the by-production of energy carriers in the subsystem of consumers,
- $\mathbf{D}_G$ – vector of the supplementary supply of energy carriers,
- $\mathbf{A}_G, \mathbf{A}_P$ – matrices of the coefficients of the consumption of energy carriers in

- the energy subsystem concerning peak and basic part of main production, respectively,
- C** – matrix of the consumption of energy carriers in the subsystem of consumers,
- I_v** – vector with elements equal 1.

By way of an example we have:

$$\mathbf{G} = \begin{bmatrix} G_1 \\ G_1 \\ \dots \\ G_n \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1p} \\ B_{21} & B_{22} & \dots & B_{2p} \\ \dots & \dots & \dots & \dots \\ B_{n1} & B_{n2} & \dots & B_{np} \end{bmatrix} \quad \mathbf{I}_v = \begin{bmatrix} 1 \\ 1 \\ \dots \\ 1 \end{bmatrix} - \text{p-vector}$$

$$\mathbf{A}_G = \begin{bmatrix} a_{11}^G & a_{12}^G & \dots & a_{1n}^G \\ a_{21}^G & a_{22}^G & \dots & a_{2n}^G \\ \dots & \dots & \dots & \dots \\ a_{n1}^G & a_{n2}^G & \dots & a_{nn}^G \end{bmatrix} \quad \mathbf{F}_G = \begin{bmatrix} 0 & f_{12}^G & \dots & f_{1n}^G \\ f_{21}^G & 0 & \dots & f_{2n}^G \\ \dots & \dots & \dots & \dots \\ f_{n1}^G & f_{n2}^G & \dots & 0 \end{bmatrix}$$

Vectors **P** and **D_G** have the same structure as vector **G**. Matrix **C** is similar to matrix **B**, and the same concerns the matrices **A_p** and **F_p** in comparison with the matrices **A_G** and **F_G**.

From the matrix equation (6.12) the vector **G** of main production is usually calculated. It concerns the description model in which vector **P** of the basic part of the main production and vector **D_G** of supplementary supply are assumed to be known a priori.

$$\mathbf{G} = (\mathbf{I} - \mathbf{A}_G + \mathbf{F}_G)^{-1} [(\mathbf{A}_p - \mathbf{F}_p)\mathbf{P} + (\mathbf{C} - \mathbf{B})\mathbf{I}_v - \mathbf{D}_G] \quad (6.13)$$

Next, the vector **D_D** of the energy carriers entirely supplied from outside is obtained:

$$\mathbf{D}_D = \mathbf{A}_{GD}\mathbf{G} + \mathbf{A}_{PD}\mathbf{P} + \mathbf{C}_D\mathbf{I}_v \quad (6.14)$$

where:

- D_D** – vector of energy carriers entirely supplied from outside,
- A_{GD}** – matrix of the coefficients of consumption of energy carriers entirely supplied from outside in the energy subsystem (peak part of production),
- A_{PD}** – matrix of the coefficients of consumption of energy carriers entirely supplied from outside in the energy subsystem (basic part of production),

$\mathbf{C}_D$ – matrix of consumption of energy carriers entirely supplied from outside in the subsystem of consumers.

By way of example we have:

$$\mathbf{D}_D = \begin{bmatrix} D_{n+1} \\ D_{n+2} \\ \dots \\ D_m \end{bmatrix} \quad \mathbf{A}_{GD} = \begin{bmatrix} a_{n+1\ 1}^{GD} & a_{n+1\ 2}^{GD} & \dots & a_{n+1\ n}^{GD} \\ a_{n+2\ 1}^{GD} & a_{n+2\ 2}^{GD} & \dots & a_{n+2\ n}^{GD} \\ \dots & \dots & \dots & \dots \\ a_{m\ 1}^{GD} & a_{m\ 2}^{GD} & \dots & a_{m\ n}^{GD} \end{bmatrix}$$

$$\mathbf{C}_D = \begin{bmatrix} a_{n+1\ 1}^D & a_{n+1\ 2}^D & \dots & a_{n+1\ p}^D \\ a_{n+2\ 1}^D & a_{n+2\ 2}^D & \dots & a_{n+2\ p}^D \\ \dots & \dots & \dots & \dots \\ a_{m\ 1}^D & a_{m\ 2}^D & \dots & a_{m\ p}^D \end{bmatrix}$$

Matrix $\mathbf{A}_{pD}$ has the same structure as matrix $\mathbf{A}_{GD}$. The inverse matrix $(\mathbf{I} - \mathbf{A}_G + \mathbf{F}_G)^{-1}$ includes elements which take into account not only the direct but also the indirect relations between energy processes in complex buildings. In order to determine the vector $\mathbf{G}$ of global production we use the equation (6.13). In the case of multi-variant calculations (varying matrices $\mathbf{C}, \mathbf{B}$ or vector $\mathbf{D}_G$) the equation (6.13) provides better possibilities. Single calculations should rather be carried out by means of equation (6.12).

6.2. Mathematical model of the balance of cumulative energy consumption

The analysis of the direct consumption of energy does not include all the energy required for the production of any given useful energy carrier (or any other product). Other energy carriers used for its production (e.g. fuels) also require the consumption of energy in intermediate processes of production and transport. Thus, every product (energy carrier) is produced not only as a result of direct but also indirect energy consumption in numerous preceding processes in the network of energy and technological interconnections. Therefore a complete energy analysis should be based on the cumulative calculus of energy consumption. The method of calculating the indices of cumulated energy consumption of energy carriers in complex buildings is based on the input-output mathematical model of the energy balance. The input data to such an analysis are the results of calculations of the balance of direct energy consumption in complex buildings and indices of cumulative energy consumption of energy carriers supplied from outside (values of the average indices of cumulative energy consumption in the energy system of an entire country).

Thus, as mentioned above, production processes (also of energy carriers) are interconnected constituting a network of mutual technological, energy and transport relations. Primary energy carriers or converted (final) energy carriers are consumed not only in the last stage of the network of processes but also in the previous ones. The sum of the direct energy consumption, and the energy used in intermediate stages and in its transport is here termed *cumulative energy consumption* (Appendix F). The index of cumulative energy consumption

can be calculated in relation to a specific final energy carrier (e.g., electricity) or primary energy (e.g. natural gas), as well as the total index of primary energy consumption (hard coal, natural gas, crude oil etc.).

The index of cumulative energy consumption of the i -th energy carrier per unit of the j -th useful product is expressed as follows [9]:

$$e_{i\ j}^* = \frac{\Delta E_i}{\Delta K_j} \quad (6.15)$$

where ΔE_i denotes the increased consumption of the i -th energy carrier (final or primary) due to the increase by ΔK_j of the useful products.

The global index of cumulative energy consumption comprises all the primary energy carriers provided by nature [9]:

$$e_j^* = \sum_p e_{p\ j}^* \quad (6.16)$$

where p denotes the kind of non-renewable primary energy.

The theory of cumulative energy consumption belongs to the class of systems methods. It can be used, among others, to compare various systems that supply buildings with energy. Energy carriers used in complex buildings may be main products or by-products of the energy subsystem of complex buildings, as well as external supplies (e.g., fuels). The index of cumulative energy consumption may be calculated separately for various forms of energy (final or primary), as well as the global index describing the overall consumption of various forms of primary energy [9]. In this book the latter definition of cumulative energy consumption is applied.

In order to determine the relations describing the indices of cumulative energy consumption, balances of cumulative energy consumption, similar to the linear mathematical model of energy management of complex buildings are set up. As energy carriers consumed in complex buildings may be, as mentioned earlier, either main or by-products, or supplied from outside (e.g. fuels), the average weighted indices of cumulative energy consumption should be applied. The cumulative energy balance concerning the j -th energy branch (peak part of production) has been presented in Figure 6.1 in a general form.

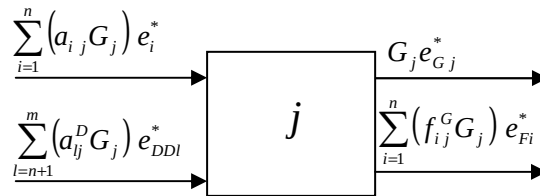


Fig. 6.1. Cumulative energy balance of the j -th energy branch (peak part of production); e_i^* - average index of cumulative energy consumption burdening the i -th energy carrier, e_{Gj}^* - index of cumulative energy consumption concerning peak production; e_{DDl}^* - index of cumulative energy consumption concerning the l -th energy carrier entirely supplied from outside; e_{Fi}^* - index of cumulative energy consumption concerning the by-products.

The average index of the i -th energy carrier is determined by the equation:

$$e_i^* = r_{Gi} e_{Gi}^* + r_{Pi} e_{Pi}^* + r_{Fi} e_{Fi}^* + r_{DGi} e_{DGi}^* \quad (6.17)$$

where:

- $r_{Gi}, r_{Pi}, r_{Fi}, r_{DGi}$ - the shares of peak and basic part of main production, by-production and external supplementary supply in the global input of the i-th energy carrier,
- e_{DGi}^* - index of cumulative energy consumption concerning the supplementary supply of the i- th energy carrier from outside.

Thus, the indices of the cumulative energy consumption of energy carriers supplied to the branch "j" are generally average weighted values of the indices of cumulative energy consumption of the main product, the by-product and supplementary supply from outside. The input values in the algorithm of the analysis of the cumulative energy consumption are indices of the cumulative consumption of energy supplied to the complex buildings from outside (mainly fuels and electricity). The indices of cumulative energy consumption concerning by-products are determined in compliance with the principle of avoided energy expenditures in the process replaced by manufacturing the by-product.

In matrix notation the set of equations of the cumulative energy balance takes the form:

$$\mathbf{A}_G^T \mathbf{e}^* + \mathbf{A}_{GD}^T \mathbf{e}_{DD}^* = \mathbf{e}_G^* + \mathbf{F}_G^T \mathbf{e}_F^* \quad (6.18)$$

where:

- $\mathbf{e}^*$ - vector of average indices of cumulative energy consumption,
- $\mathbf{e}_{DD}^*$ - vector of indices of cumulative energy consumption concerning energy carriers entirely supplied from outside,
- $\mathbf{e}_G^*$ - vector of average indices of cumulative energy consumption concerning the peak part of the main production of energy carriers,
- $\mathbf{e}_F^*$ - vector of average indices of cumulative energy consumption concerning the by-production of energy carriers.

Similarly, the balancing of cumulative energy of the basic part of production takes the following form:

$$\mathbf{A}_P^T \mathbf{e}^* + \mathbf{A}_{PD}^T \mathbf{e}_{PD}^* = \mathbf{e}_P^* + \mathbf{F}_P^T \mathbf{e}_F^* \quad (6.19)$$

where $\mathbf{e}_P^*$ denotes the vector of indices of cumulative energy consumption concerning the basic part of main production of energy carriers.

The vector of average indices of cumulative energy consumption is expressed by the equation:

$$\mathbf{e}^* = \mathbf{r}_G^d \mathbf{e}_G^* + \mathbf{r}_P^d \mathbf{e}_P^* + \mathbf{r}_F^d \mathbf{e}_F^* + \mathbf{r}_{DG}^d \mathbf{e}_{DG}^* \quad (6.20)$$

where:

- $\mathbf{r}_G^d$ - diagonal matrix of the shares of the peak part of main production,
- $\mathbf{r}_P^d$ - diagonal matrix of the shares of the basic part of main production,
- $\mathbf{r}_F^d$ - diagonal matrix of the shares of by-production of energy carriers,

$\mathbf{r}_{DG}^d$ - diagonal matrix of the shares of supplementary supplies of energy carriers,

$\mathbf{e}_{DG}^*$ - vector of indices of cumulative energy consumption concerning supplementary supplies of energy carriers.

Equations (6.18), (6.19) and (6.20) constitute the algorithm of calculating the indices of cumulative energy consumption concerning energy carriers produced in the energy subsystem of complex buildings.

The input data for the procedure of calculating the coefficients of cumulative energy consumption in complex buildings result from the energy balance of the building and the coefficients of cumulative energy consumption of energy carriers supplied to the complex buildings. These vectors result from the analysis of the cumulative energy consumption concerning the entire energy management of a country. The vector $\mathbf{e}_F^*$ of the indices of cumulative energy consumption charging the by-products is, as already mentioned, assessed based on the principle of replacing the main products by by-products in compliance with the method of avoided energy expenditures.

The cumulative energy balance concerning the k-th branch of the subsystem of consumers has the form presented in Figure 6.2.

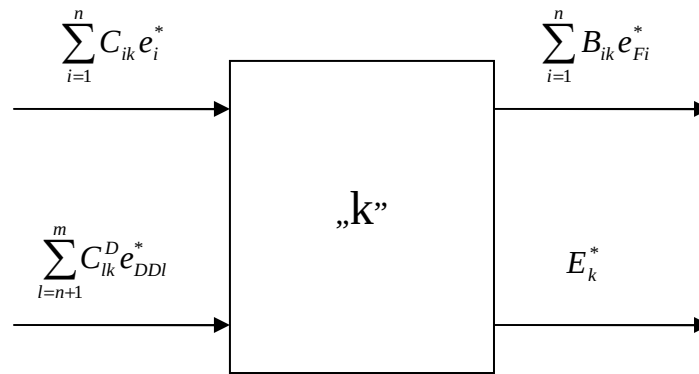


Fig.6.2. Cumulative energy balance of the k-th branch of the subsystem of consumers; E_k^* denotes the cumulative energy consumption concerning the k-th branch of consumers (e.g. office rooms, garages, etc.)

The set of cumulative energy balances of branches of the subsystem of consumers has the following form in matrix notation:

$$\mathbf{E}^* = \mathbf{C}^T \mathbf{e}^* + \mathbf{C}_D^T \mathbf{e}_{DD}^* - \mathbf{B}^T \mathbf{e}_F^* \quad (6.21)$$

where $\mathbf{E}^*$ denotes the vector concerning cumulative energy consumption of the subsystem of consumers.

The vector $\mathbf{e}^*$ of the average indices of cumulative energy concerning energy carriers produced in the energy subsystem of complex buildings results from Eq.(6.20). The vector $\mathbf{e}_{DD}^*$ of indices of cumulative energy consumption of energy carriers entirely supplied from outside is known a priori, and the vector $\mathbf{e}_F^*$ concerning the by-production of energy carriers in the subsystem of consumers results from the principle of avoided energy expenditure.

6.3. Mathematical model of the analysis of cumulative emissions in complex buildings

The exploitation of complex buildings generates direct and indirect emissions of noxious substances (gases, liquids and solid wastes) to the environment. These emissions should be minimised by an appropriate design and exploitation of the buildings. The direct consumption of energy carriers (mainly fuels) leads to direct emissions connected with the production of the given energy carrier. But these energy carriers, supplied to complex buildings, are already charged with noxious emissions resulting from previous stages of production and their transport [5]. As is the case with cumulative energy consumption, this is due to the existence of mutual connections in the energy-technological network. Thus, the ecological charge of the given energy carrier consumed in complex buildings depends not only on the direct emission but also on emissions which occurs in the course of previous processes and transport. Therefore, as is the case with indices of cumulative energy carriers, indices of cumulative emissions should be applied.

Cumulative emissions of noxious substances can be used as a measure of the influence of the complex buildings on the environment. Cumulative emissions may be defined as the sum of direct and indirect emissions caused in the course of production, transport, preparation and consumption of energy carriers which are essential for the exploitation of the building. Indices of cumulative emissions can be calculated by means of a set of linear energy balances of the building. The concept of the balance of cumulative emissions in complex buildings is presented in Figure 6.3.

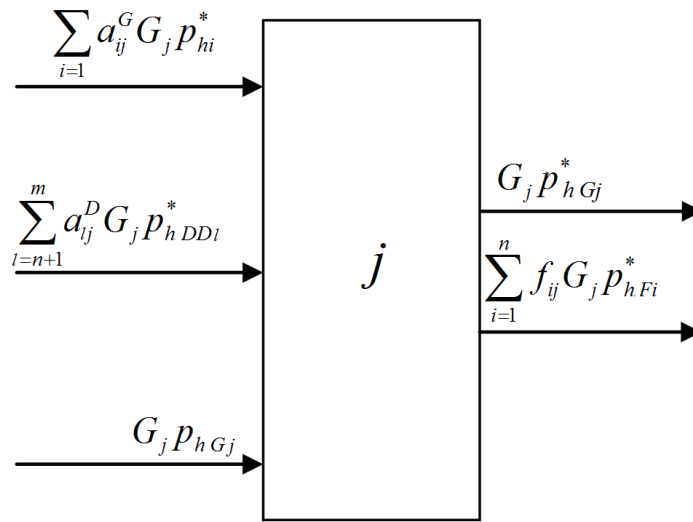


Fig. 6.3. Flow chart of the balance of the h-th kind of cumulative emissions of the j-th energy branch (peak part of the production)

The average weighted index of cumulative emissions of h-th kind of emissions charging the i-th main product (peak part) is calculated by means of the following formula:

$$p_{hi}^* = r_{Gi} p_{hGi}^* + r_{Pi} p_{hPi}^* + r_{Fi} p_{hFi}^* + r_{Di} p_{hDGi}^* \quad (6.22)$$

where:

r_{Gi} , r_{Pi} , r_{Fi} , r_{Di} - the shares of main production (peak and basic part), by-production and external supplementary supply in h-th kind of emissions of the i-th energy carrier.

p_{hGi}^* , p_{hGj}^* - the h-th kind of cumulative emission burdening the peak production of the i-th or j-th energy carrier,

p_{hPi}^* - the h-th kind of cumulative emission burdening the basic part of the i-th energy carrier,
 p_{hFi}^* - the h-th kind of cumulative emission burdening the by-production of energy carriers,
 p_{hDGi}^* - the h-th kind of cumulative emission concerning the i-th supplementary supply of energy carriers,
 p_{hDDl}^* - the h-th kind of cumulative emission concerning the l-th energy carriers entirely supplied from outside,
 p_{hGj} - the h-th kind of direct emission in the j-th energy branch.

Basing on the idea presented in Figure 6.3, the input-output balance equation of cumulative emissions in complex buildings concerning the peak part of the main production takes the form in matrix notation:

$$\mathbf{A}_G^T \mathbf{p}_h^* + \mathbf{A}_{GD}^T \mathbf{p}_{hDD}^* + \mathbf{p}_{hG} = \mathbf{p}_{hG}^* + \mathbf{F}_G^T \mathbf{p}_{hF}^* \quad (6.23)$$

where:

$\mathbf{p}_h^*$ – vector of average coefficients of the h-th kind cumulative emissions,
 $\mathbf{p}_{hDD}^*$ – vector of the coefficients of the h-th kind of cumulative emissions concerning energy carriers entirely supplied from outside,
 $\mathbf{p}_{hG}$ – vector of the coefficients of the h-th kind of direct emissions in energy branches (peak part of the production),
 $\mathbf{p}_{hG}^*$ – vector of the coefficients of the h-th kind of cumulative emissions burdening the peak part of the main production of energy carriers,
 $\mathbf{p}_{hF}^*$ – vector of the coefficients of the h-th kind of cumulative emissions burdening the by-production of energy carriers.

By way of example we have:

$$\mathbf{p}_h^* = \begin{bmatrix} P_{h1}^* \\ P_{h2}^* \\ \dots \\ P_{hn}^* \end{bmatrix} - \text{n-vector} \quad \mathbf{p}_{hDD}^* = \begin{bmatrix} P_{hDD(n+1)}^* \\ P_{hDD(n+2)}^* \\ \dots \\ P_{hDDm}^* \end{bmatrix} - \text{m-vector}$$

The vectors $\mathbf{p}_{hG}$, $\mathbf{p}_{hG}^*$ and $\mathbf{p}_{hF}^*$ have the same structure as the vector $\mathbf{p}_h^*$.

Similarly, the balancing of cumulative emissions concerning the basic part of the main production takes the following form in matrix notation:

$$\mathbf{A}_P^T \mathbf{p}_h^* + \mathbf{A}_{PD}^T \mathbf{p}_{hDD}^* + \mathbf{p}_{hP} = \mathbf{p}_{hP}^* + \mathbf{F}_P^T \mathbf{p}_{hF}^* \quad (6.24)$$

where:

$\mathbf{p}_{hP}$ - vector of the coefficients of the h-th kind of direct emissions in energy branches (basic part of production),
 $\mathbf{p}_{hP}^*$ - vector of the coefficients of the h-th cumulative emissions burdening the basic part of the main production of energy carriers.

The structure of the vectors $\mathbf{p}_{hP}$ and $\mathbf{p}_{hP}^*$ is the same as that of the vectors $\mathbf{p}_{hG}$ and $\mathbf{p}_{hG}^*$.

The vector of average coefficients of the h-th kind of cumulative emissions is expressed by the equation:

$$\mathbf{p}_h^* = \mathbf{r}_G^d \mathbf{p}_{hG}^* + \mathbf{r}_P^d \mathbf{p}_{hP}^* + \mathbf{r}_F^d \mathbf{p}_{hF}^* + \mathbf{r}_{DG}^d \mathbf{p}_{hDG}^* \quad (6.25)$$

where $\mathbf{p}_{hDG}^*$ denotes the vector of coefficients of the h-th kind of cumulative emissions concerning supplementary supplies of energy carriers from outside.

Eqs.(6.23), (6.24) and (6.25) constitute the algorithm of calculating the coefficients of the h-th kind of cumulative emissions concerning energy carriers produced in the energy subsystem of complex buildings. The vectors of cumulative h-th emissions $\mathbf{p}_{hDD}^*$ and $\mathbf{p}_{hDG}^*$ connected with external supplies are given a priori, previously determined based on the analysis of cumulative emissions all over the country [8,9]. The vector of cumulative h-th emissions $\mathbf{p}_{hF}^*$ concerning the by-production is determined in compliance with the principle of avoided emissions.

The flow chart of the h-th kind of cumulative emissions of the k-th branch of the subsystem of consumers has the form presented in Figure 6.4.

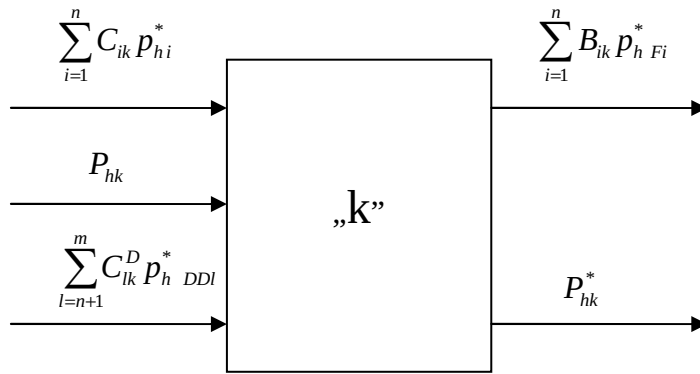


Fig.6.4. Flow chart of the h-th kind of cumulative emissions of the k-th branch of the subsystem of energy consumers; P_{hk} - direct emission of the h-th kind of the k-th branch of subsystem of consumers

The set of equations concerning the h-th kind of cumulative emissions of the branches of the subsystem of consumers has the following form in matrix notation:

$$\mathbf{P}_h^* = \mathbf{C}^T \mathbf{p}_h^* + \mathbf{C}_D^T \mathbf{p}_{hDD}^* + \mathbf{P}_h - \mathbf{B}^T \mathbf{p}_{hF}^* \quad (6.26)$$

where:

$\mathbf{P}_h^*$ – p-vector of cumulative emissions of the h-th emissions of subsystem of consumers,

$\mathbf{P}_h$ – p-vector of direct emissions of the h-th emissions of subsystem of consumers.

By way of example we have:

$$\mathbf{P}_h^* = \begin{bmatrix} P_{h1}^* \\ P_{h2}^* \\ \dots \\ P_{hp}^* \end{bmatrix} - p - vector$$

The vector $\mathbf{P}_h$ has the same structure as the vector $\mathbf{P}_h^*$.

The vector $\mathbf{p}_h^*$ of average coefficients of the h-th kind of cumulative emissions concerning energy carriers produced in the energy subsystem of complex buildings results from Eq.(6.25). The vector $\mathbf{p}_{hDD}^*$ of the coefficients of the h-th kind of cumulative emissions of energy carriers entirely supplied from outside is known a priori, and the vector $\mathbf{p}_{hF}^*$ concerning the by-production of energy carriers in the subsystem of consumers results from the principle of avoided emissions.

6.4. Mathematical model for the analysis of thermo-ecological costs

The construction and exploitation of complex buildings is possible thanks to the consumption of non-renewable natural resources. The minimisation of the depletion of non-renewable natural resources is becoming more and more crucial to the sustainable development of humankind [10,12]. The quality of non-renewable natural resources can be evaluated using exergy, because the composition and concentration of natural resources differ from the values commonly occurring in the environment [11]. The cumulative consumption of the exergy of non-renewable natural resources, connected with manufacturing the considered product under consideration, can be used as a measure of the depletion of non-renewable natural resources connected with the construction and exploitation of complex buildings. This measure has been termed the thermo-ecological cost of the particular product. The thermo-ecological cost can be defined as the cumulative consumption of exergy of non-renewable natural resources connected with manufacturing a particular product, including additional consumption due to the necessity of compensating the environmental losses caused by the release of harmful emissions. The indices of the thermo-ecological cost can be calculated by means of linear balance equations of the thermo-ecological cost [9,10].

The concept of the thermoecological cost balance equation is explained in Figure 6.5. The balance equation thermo-ecological cost for the j-th energy branch includes [9,10]:

- thermo-ecological cost of domestic energy carriers and semi-finished products,
- thermo-ecological cost of imported goods,
- direct exergy consumption of non-renewable natural resources (thermo-ecological cost of natural resources),
- thermo-ecological cost of emissions,
- thermo-ecological cost of the main product,
- thermo-ecological cost of by-products; the by-production of goods that replace other useful products (e.g., the cooling medium from the trigeneration unit that replaces the cooling medium from the refrigerating unit) results in the decrease of the thermo-ecological cost of main products.

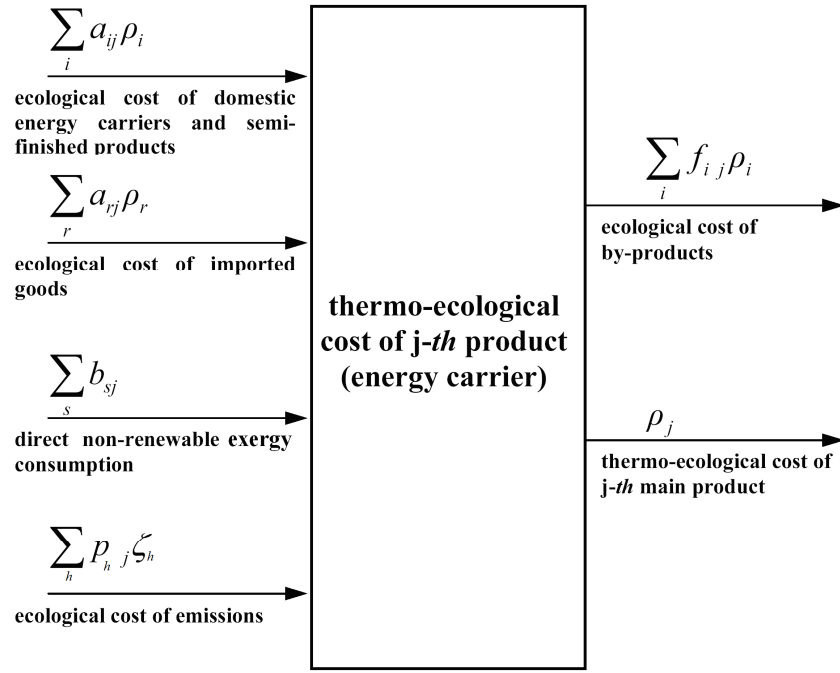


Fig. 6.5. Structure of the thermo-ecological cost balance equation [8]

Based on the idea of thermo-ecological cost calculations [12,13], the input-output thermo-ecological cost balance equation for the j -th energy branch in complex buildings takes the form:

$$\rho_j + \sum_i f_{ij} \rho_{iF} = \sum_i a_{ij} \rho_i + \sum_r a_{rj} \rho_r + \sum_s b_{sj} + \sum_h p_{hj} \zeta_h \quad (6.27)$$

where:

- ρ_j, ρ_i – specific thermo-ecological costs of the j -th or i -th product (energy carrier),
- ρ_{iF} – specific thermo-ecological cost of the by-product,
- a_{ij} – coefficient of the consumption of the i -th product,
- f_{ij} – coefficient of the by-production,
- a_{rj} – coefficient of the consumption of an imported product,
- ρ_r – thermo-ecological cost of the imported r -th raw materials and semi-products,
- b_{sj} – exergy of the s -th non-renewable natural resource consumed directly in the j -th process,
- p_{hj} – amount of the harmful h -th waste component,
- ζ_h – exergy consumption of non-renewable natural resources due to h -th emission.

The additional exergy consumption ζ_h of non-renewable natural resources due to emissions of waste products is as follows [9,12]:

$$\zeta_h = \frac{B w_h}{GDP + \sum_h P_h w_h} \quad (6.28)$$

where:

- B – annual consumption of the non-renewable exergy,
- w_h – monetary index of harmfulness of the h-th waste product,
- GDP – gross domestic product,
- P_h – annual emissions of the h-th waste product in the whole country.

The thermo-ecological cost of imported goods is calculated taking into account the related thermo-ecological cost of exported products and semi-products. Assuming that the thermo-ecological cost of imported raw materials and semi-products relates to the same monetary units the as those for exported goods [9,12], we can write:

$$\rho_r = \frac{\sum_i S_i \rho_i}{\sum_i S_i D_i} D_r \quad (6.29)$$

where:

- S_i – amount of the i-th exported product,
- ρ_i – coefficient of the thermo-ecological cost of the i-th exported product,
- D_i – value of foreign exchange of the i-th exported product,
- D_r – value of foreign exchange of the r-th imported product.

In order to obtain exact results, this set of equations (6.27) should take into account all the branches of the economy of the country. Such an approach requires, however, a considerably extended input data base. As some parts of interconnections between the branches of the economy of the country are weak connections, the set of equations (6.27) can be solved only concerning branches with strong interconnections. The indices of the thermo-ecological costs of fundamental products (e.g., fuels, raw material, steel, cement, electricity) determined in this way, may later be applied, making use of the sequential method, in calculations of the thermo-ecological costs concerning products of branches weakly interconnected with the fundamental ones. This method may be iterated in to order to improve the results of the first approximation. Such an approach is applied in the analysis of the thermo-ecological costs of complex buildings, concerning both the energy subsystem and the subsystem of consumers.

The balance of thermo-ecological cost concerning the j-th energy branch (peak part of production) of complex buildings has been presented in Figure 6.6.

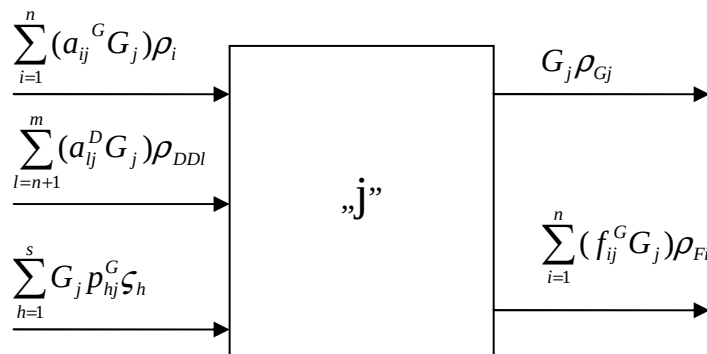


Fig.6.6. The balance of thermo-ecological cost of the j-th branch (peak part of production); ρ_i - average index of thermo-ecological cost of the i-th energy carrier; ρ_{DDl} - index of thermo-ecological cost concerning the l-th energy carrier entirely supplied from outside; ρ_{Gj} - index of thermo-ecological cost concerning the peak part of production of the energy carriers; ρ_{Fi} - index of thermo-ecological cost of the i-th by-product; p_{hj}^G - the h-th kind of emission burdening the j-th branch (peak part of the production); ζ_h - additional exergy consumption of non-renewable natural resources due to the h-th kind of emission; s- number of the considered kinds of emissions.

The average index of thermo-ecological cost of the i-th energy carrier is determined by the equation:

$$\rho_i = r_{Gi} \rho_{Gi} + r_{Pi} \rho_{Pi} + r_{Fi} \rho_{Fi} + r_{DGi} \rho_{DGi} \quad (6.30)$$

where:

r_{Gi} , r_{Pi} , r_{Fi} , r_{DGi} - the shares of the peak and basic part of the main production, by-production and external supplementary supply in the global input of the i-th energy carrier,

ρ_{Pi} - index of thermo-ecological cost of the basic part of the production of the i-th energy carrier,

ρ_{DGi} - index of thermo-ecological cost concerning the supplementary supply of the i-th energy carrier.

In matrix notation the set of input-output equations concerning the thermo-ecological costs of the peak part of the production takes the form:

$$\mathbf{A}_G^T \mathbf{p} + \mathbf{A}_{GD}^T \mathbf{p}_{DD} + \mathbf{p}_G^T \boldsymbol{\zeta} = \mathbf{p}_G + \mathbf{F}_G^T \mathbf{p}_F \quad (6.31)$$

where:

$\mathbf{p}$ - vector of the average indices of the thermo-ecological costs,

$\mathbf{p}_{DD}$ - vector of indices of thermo-ecological costs concerning energy carriers entirely supplied from outside,

$\mathbf{p}_G$ - vector of indices of thermo-ecological costs of the peak part of the main production of energy carriers,

$\mathbf{p}_F$ - vector of indices of thermo-ecological costs concerning the by-production of energy carriers,

$\mathbf{p}_G$ - matrix of direct emissions concerning the peak part of the main production,

ζ - vector of additional exergy consumption of natural resources due to emissions.

By way of example we have:

$$\mathbf{p} = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \dots \\ \rho_n \end{bmatrix} - \text{n-vector} \quad \mathbf{p}_{DD} = \begin{bmatrix} \rho_{n+1} \\ \rho_{n+2} \\ \dots \\ \rho_m \end{bmatrix} - \text{m-vector}$$

$$\mathbf{p}_G = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \dots & \dots & \dots & \dots \\ p_{s1} & p_{s2} & \dots & p_{sn} \end{bmatrix} \quad \zeta = \begin{bmatrix} \zeta_1 \\ \zeta_2 \\ \dots \\ \zeta_s \end{bmatrix} - \text{s-vector}$$

The vectors $\mathbf{p}_G$ and $\mathbf{p}_F$ have the same structure as the vector $\mathbf{p}$.

Similarly, the balancing of thermo-ecological cost of the basic part of the main production takes the following form:

$$\mathbf{A}_P^T \mathbf{p} + \mathbf{A}_{PD}^T \mathbf{p}_{DD} + \mathbf{p}_P^T \zeta = \mathbf{p}_P + \mathbf{F}_P^T \mathbf{p}_F \quad (6.32)$$

where:

$\mathbf{p}_P$ - vector of indices of thermo-ecological costs concerning the basic part of the main production of energy carriers,

$\mathbf{p}_P$ - matrix of direct emissions concerning the basic part of the main production.

The vector $\mathbf{p}_P$ has the same structure as the vector $\mathbf{p}_G$ and the matrix $\mathbf{p}_P$ is similar to the matrix $\mathbf{p}_G$.

The vector of average indices of thermo-ecological cost is expressed by the equation:

$$\mathbf{p} = \mathbf{r}_G^d \mathbf{p}_G + \mathbf{r}_P^d \mathbf{p}_P + \mathbf{r}_F^d \mathbf{p}_F + \mathbf{r}_{DG}^d \mathbf{p}_{DG} \quad (6.33)$$

where $\mathbf{p}_{DG}$ denotes the vector of thermo-ecological cost concerning supplementary supply of energy carriers from outside.

Equations (6.31), (6.32) and (6.33) constitute the algorithm of calculating the indices of thermo-ecological costs concerning energy carriers produced in the energy subsystem of complex buildings. The vectors $\mathbf{p}_{DD}$ and $\mathbf{p}_{GD}$ concerning thermo-ecological costs of external supplies are known a priori from the thermo-ecological analysis of main products in the economy of the whole country. The vector $\mathbf{p}_F$ of indices of thermo-ecological costs of by-

products is also known based on the principle of avoided expenditures (the by-product should be burdened with the consumption of semi-products and energy carriers avoided in the substituted process thanks to the utilisation of the considered by-product).

The balance of thermo-ecological cost concerning the k-th branch of the subsystem of consumers has the form presented in Figure 6.7.

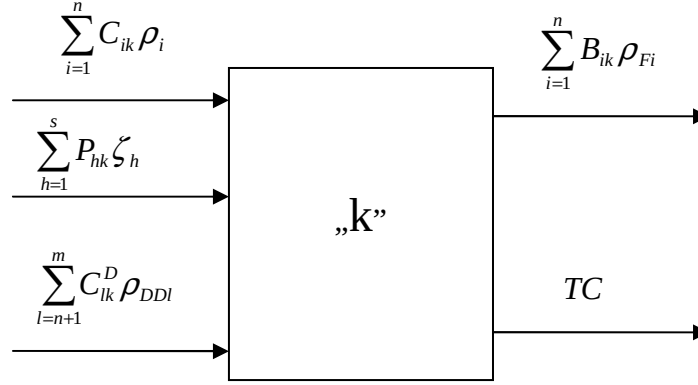


Fig.6.7. The balance of thermo-ecological cost of the k-th branch of the subsystem of consumers; P_{hk} - the h-th kind of direct emission of the k-th branch of consumers;

TC - thermo-ecological costs concerning the k-th branch of consumers.

The set of thermo-ecological balances of branches of the subsystem of consumers has the following form in matrix notations:

$$\mathbf{TC} = \mathbf{C}^T \mathbf{p} + \mathbf{C}_D^T \mathbf{p}_{DD} + \mathbf{P}^T \boldsymbol{\zeta} - \mathbf{B}^T \mathbf{p}_F \quad (6.34)$$

where:

$\mathbf{TC}$ - vector of thermo-ecological costs of the subsystem of consumers,

$\mathbf{P}$ - matrix of direct emissions concerning the subsystem of consumers.

By way of example we have

$$\mathbf{P} = \begin{bmatrix} P_{11} & \dots & P_{1k} & \dots & P_{1p} \\ \dots & \dots & \dots & \dots & \dots \\ P_{h1} & \dots & P_{hk} & \dots & P_{hp} \\ \dots & \dots & \dots & \dots & \dots \\ P_{s1} & \dots & P_{sk} & \dots & P_{sp} \end{bmatrix} \quad \mathbf{TC} = \begin{bmatrix} TC_1 \\ TC_2 \\ \dots \\ TC_p \end{bmatrix}$$

The vector $\mathbf{p}$ of average indices of thermo-ecological costs concerning energy carriers produced in the energy subsystem of complex buildings results from Eq.(6.33). The vector

$\mathbf{p}_{DD}$ of indices of the thermo-ecological costs of energy carriers entirely supplied from outside is known a priori. The vector $\mathbf{p}_F$ concerning indices of the thermo-ecological costs of by-products results from the principle of avoided expenditures as mentioned above in the discussion concerning Eqs. (6.31) - (6.33).

6.5 Algorithm of the system evaluation of the rationalisation of the energy management of a complex buildings

Due to interconnections between energy branches, the rationalisation carried out in one process influences other processes. For this reason the process method of the evaluation of the effect of energy rationalisation does not take into account the interdependences existing between energy processes. Therefore, this method provides incomplete energy effects of energy rationalisation. The systems approach is necessary in this case. The energy effects of energy rationalisation in an energy subsystem or subsystem of consumers should be determined at the balance shield of the system of complex buildings. In this way, direct and indirect connections between the processes under consideration, where the energy rationalisation is carried out, and other processes will be taken into account [16,17].

The systems analysis of the effect of energy rationalisation on the energy management of complex buildings is based on the mathematical model of the energy management of complex buildings. The energy rationalisation may be realised either in the energy subsystem or in the subsystem of consumers. The direct effects of this rationalisation are evaluated by means of process methods (e.g., changing the separate production of heat and electricity into cogeneration). System effects of energy rationalisation are achieved by applying the inverse matrix of the set of energy balance equations, the coefficients of which concern both direct and indirect consumption resulting from connections in the network of energy processes.

A process change in any given part of the energy subsystem or the subsystem of consumers involves changes in the remaining parts due to interconnections in the energy management of complex buildings. The system of interconnections is expressed by the set of balance equations (6.12) and (6.14) which may be reduced to the following form:

$$\mathbf{G} + \mathbf{F}_G \mathbf{G} + \mathbf{D}_G = \mathbf{A}_G \mathbf{G} + \mathbf{C} \mathbf{I}_v \quad (6.35)$$

$$\mathbf{D}_D = \mathbf{A}_{GD} \mathbf{G} + \mathbf{C}_D \mathbf{I}_v \quad (6.36)$$

A comparison with the Eqs.(6.12) and (6.14) it has been assumed that neither a by-production in subsystem of consumers, nor a division of the main production into basic and peak part do exist.

From the Eqs.(6.35) and (6.36) we get:

$$\mathbf{G}=(\mathbf{I}-\mathbf{A}_G+\mathbf{F}_G)^{-1}(\mathbf{C} \mathbf{I}_v-\mathbf{D}_G) \quad (6.37)$$

$$\mathbf{D}_D=\mathbf{A}_{GD}(\mathbf{I}-\mathbf{A}_G+\mathbf{F}_G)^{-1}(\mathbf{C} \mathbf{I}_v-\mathbf{D}_G)+\mathbf{C}_D \mathbf{I}_v \quad (6.38)$$

If the process change occurs in the subsystem of consumers, the vectors $\mathbf{C}_G$ and $\mathbf{C}_D$ change, too, and we get:

$$\Delta \mathbf{G}=(\mathbf{I}-\mathbf{A}_G+\mathbf{F}_G)^{-1}[(\mathbf{C} \mathbf{I}_v-\mathbf{D}_G)''-(\mathbf{C} \mathbf{I}_v-\mathbf{D}_G)'] \quad (6.39)$$

$$\Delta \mathbf{D}_D=\mathbf{A}_D \Delta \mathbf{G}+(\mathbf{C}_D''-\mathbf{C}_D') \mathbf{I}_v \quad (6.40)$$

The inverse matrix $(\mathbf{I}-\mathbf{A}_G+\mathbf{F}_G)^{-1}$ comprises the entire system of interconnections of the energy branches belonging to the technological network. In this way direct and indirect connections between energy carriers have been taken into account. The application of the inverse input-output matrix eliminates the laborious method of making successive approximations in investigations of the influence of rationalisation in the subsystem of energy or subsystem of consumers upon the energy systems of complex buildings as a whole. The apostrophes '' and ' denote the state of the energy management of complex buildings after and before to its rationalisation.

In the case of changes in the energy subsystem the element of the matrices $\mathbf{A}_G$ and $\mathbf{F}_G$ are changed, and then:

$$\Delta \mathbf{G}=[(\mathbf{I}-\mathbf{A}_G''+\mathbf{F}_G'')^{-1}-(\mathbf{I}-\mathbf{A}_G'+\mathbf{F}_G')^{-1}](\mathbf{C} \mathbf{I}_v-\mathbf{D}_G) \quad (6.41)$$

$$\Delta \mathbf{D}_D=\mathbf{A}_D \Delta \mathbf{G} \quad (6.42)$$

In this case a change of the inverse matrix also permits to evaluate the system effects.

In conclusion, the usually applied process method of evaluating the energy effects of rationalisation in energy systems of complex buildings does not allow to take into account the energy effects of the network relations between energy processes. The application of the mathematical model of energy management of complex buildings in the systems approach to the evaluation of rationalisation effects makes it possible to take into account all the interdependences between the energy processes in order to obtain accurate results. The system energy effects of rationalising the energy management of complex buildings are determined at the balance shield of complex buildings. The final results of this calculation are usually changes in the external supplies of energy carriers due to the rationalisation of their consumption.

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Chapter 7

SYSTEMS ANALYSIS OF THE EXPLOITATION OF ENERGY MANAGEMENT IN COMPLEX BUILDINGS – EXAMPLES OF APPLICATIONS

Chapter 7 is devoted to practical applications of the mathematical models described in the previous chapter.

The analysis in this chapter concerns an typical office building situated in Warsaw. The subsystem of consumers comprises office rooms, auxiliary rooms, garages and standard equipment of the building. Six kinds of energy carriers are produced in the energy subsystem, viz., the cooling agent, hot process water with a temperature of 85/55° C and 60/45° C, hot tap water, air from the air-conditioning unit, and ventilation air for the garages. Electricity, heat, natural gas and drinking water are supplied entirely from outside. The annual energy balance has been set up according to the input-output model of direct energy consumption. The balance of cumulative energy consumption has been struck based on the values of the indices of cumulative energy consumption of supplies from outside. The share of office rooms in the total cumulative energy consumption of the office building under consideration amounts to about two thirds. Cumulative energy consumption is dominated by electricity, which exceeds 75 per cent of the total. The share of cumulative energy consumption which burdens the heat from the heating plant amounts to about 20 per cent. The analysis of cumulative emissions concerns NO_x and CO₂. The input data are indices of cumulative emissions burdening the supplies from outside. In the case of both NO_x and CO₂ emissions, office rooms dominate (accounting for more than 50 per cent of those emissions). The analysis of thermo-ecological costs, like the analyses of cumulative energy consumption and cumulative emissions, is based on the principle of weak connections and denotes that office rooms also account for more than 50 per cent of those costs, and electricity and heat supplied from outside amount to about 96.5 per cent of the thermo-ecological cost of the analysed office building (68.4 per cent of electricity and 27.6 per cent of heat from the heating plant).

A systems analysis was also carried out concerning the rationalisation of energy management in this building, both for the subsystem of consumers and the energy subsystem, via:

- the application of night cooling ventilation,
- the application of a small-scale CHP unit equipped with a piston engine.

Night cooling ventilation decreases the production of the cooling medium. This leads to system changes, the final effect of which is a reduction in the electricity supply. With a CHP

unit, the structure of the energy subsystem in the office building changes due to the replacement of the supply of heat, and partially of electricity. Savings in the chemical energy of fuels, compared with the separate production of heat and electricity, lead to the index PES (Primary Energy Savings) amounting to 31 per cent, which proves the high energy effectivity of modernising the energy management in the office building under consideration.

7.1. Description of a case-study building

The linear mathematical model described in chapter 6 was applied to analyse a case-study complex building. This is a typical office building completed in 1999. The seven-floor building provides mainly office services. The floor area of the offices in the building is 8000 m². The building also includes car-park floors, which are neither heated nor cooled. They are only ventilated by a mechanical extract ventilation system. In this building there are two types of rooms, viz., offices with fan-coil units and auxiliary rooms with a traditional central heating system.

The fan-coil system is one of the air-conditioning systems used in the building. Fan units are placed in each office which needs to be heated or cooled. This system, used in room units, contains such components as fans, heating and cooling coils, filters and controls. This is a four-pipe system utilising two independent coils, one for heating and one for cooling. Cooling and heating valves for controlling the coil capacities are installed with their controls in the rooms. A central plant delivers hot or cold water to the fan units. A heat distribution centre produces hot water (60/45° C) in winter, and a refrigerating unit produces the cooling medium (water with glycol 6/12° C) in the summer. The fan of each unit draws air from the room, blows it over the water coil and returns it to the room. The mechanical ventilation system operates only during office hours.

The main air-conditioning unit for the building is situated on the seventh floor, and delivers a suitable quantity of air to all rooms, that is 22,500 m³/h. It is equipped with an exhaust and downcast fan (electric power: 15kW, 11kW), heater, cooler, filters, silencers, recuperator, and controls which ensure a constant temperature of 18° C ±2 K deg over the whole year. Fresh air is supplied to the offices and auxiliary rooms (30 m³/h-person), and stale air is extracted from the toilets and kitchens. The air-conditioning unit prepares only supplied air; individual temperature conditions are ensured by fan-coil units in the offices and the central heating system in auxiliary rooms. Heat is supplied to the building from a heat plant by a heat distribution network. In the building heat is distributed by the heat distribution centre, which contains three exchangers: for hot tap water (the maximum heating

power of this exchanger being 39kW), process water (293 kW), and the central heating system (100 kW). The installation of hot process water supplies heat to the heater in the air-conditioning unit and to the offices via the fan-coil units. Heat is supplied to the auxiliary rooms by the central heating system.

Car parking is situated on four floors which contain 230 parking places. These floors are only ventilated by a mechanical extract ventilation system, which works day and night (the total electrical power of exhaust fans is 19.3 kW during the day and 5 kW at night). The car park consumes electricity only for lighting, controls and monitoring.

The operation of the case-study building is related to the consumption of the following external energy carriers: electricity, heat from the district heating system, natural gas and drinking water. Fig. 7.1 shows connections between the energy carriers which are supplied to the analysed building and those produced in it.

The energy subsystem produces the following energy carriers:

- cooling medium (water–glycol) 6/12° C,
- hot process water (for the central heating system and the air-conditioning unit) 85/55 °C,
- hot tap water,
- hot process water 60/45 °C (for fan-coil units),
- air from the air-conditioning unit.

The subsystem of consumers includes:

- office rooms with fan-coil air-conditioning,
- auxiliary rooms with a traditional central heating system,
- standard building equipment such as emergency systems, fire sensors and external lighting,
- car park with a mechanical extract ventilation system.

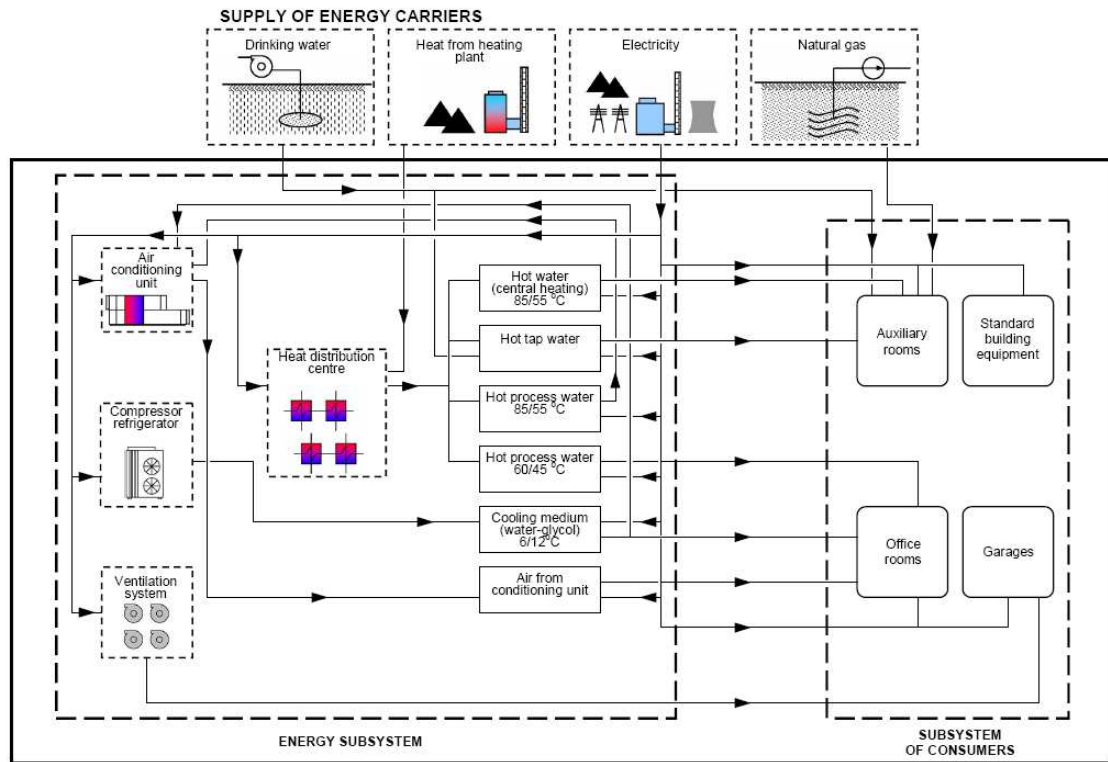


Fig. 7.1. Network of interdependences existing in a real complex building between the energy subsystem and subsystem of consumers

7.2. Systems analysis of direct energy consumption in the investigated complex building

A linear mathematical model of the energy balance of the complex building under investigation has been formulated based on the general model described in Chapter 6. Table 7.1 shows the input-output table of interbranch flows constructed for the complex building. In the case of this building the consumption of energy carriers in the subsystem of consumers is constant, imposed by the energy characteristics of the rooms.

Table 7.1. Input-output table constructed for the complex building

	Energy carriers	Unit	Production G	Supply D	AG										Subsystem of consumers			
					1	2	3	4	5	6	7	8	9	10	Office rooms	Auxiliary rooms	Garages	Standard equipment of building
															1	2	3	4
1	Cooling medium (water- glycol) 6/12°C	GJ	G ₁						Z _{1 5} ^G						$\overline{Z}_{1 1}^G$			
2	Hot process water 85/55 °C	GJ	G ₂						Z _{2 5} ^G							$\overline{Z}_{2 2}^G$		
3	Hot tap water	t	G ₃													$\overline{Z}_{3 2}^G$		
4	Hot process water (fan coil) 60/45 °C	GJ	G ₄												$\overline{Z}_{4 1}^G$			
5	Air from conditioning unit	t	G ₅												$\overline{Z}_{5 1}^G$	$\overline{Z}_{5 2}^G$		
6	Ventilation air for garages	t	G ₆														$\overline{Z}_{6 3}^G$	
7	Electricity	GJ		D ₇	Z _{7 1} ^D	Z _{7 2} ^D	Z _{7 3} ^D	Z _{7 4} ^D	Z _{7 5} ^D	Z _{7 6} ^D					$\overline{Z}_{7 1}^D$	$\overline{Z}_{7 2}^D$	$\overline{Z}_{7 3}^D$	$\overline{Z}_{7 4}^D$
8	Drinking water	t		D ₈			Z _{8 3} ^D									$\overline{Z}_{8 2}^D$		
9	Network natural gas	GJ		D ₉												$\overline{Z}_{9 2}^D$		
10	Heat from heat plant	GJ		D ₁₀		Z _{10 2} ^D	Z _{10 3} ^D	Z _{10 4} ^D										

Column vectors C_1, C_2, C_3, C_4 , separated from Table 7.1:

$$C_1 = \begin{bmatrix} \overline{Z}_{1 1}^G \\ 0 \\ 0 \\ \overline{Z}_{4 1}^G \\ \overline{Z}_{5 1}^G \\ 0 \\ \overline{Z}_{7 1}^D \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_2 = \begin{bmatrix} 0 \\ \overline{Z}_{2 2}^G \\ \overline{Z}_{3 2}^G \\ 0 \\ \overline{Z}_{5 2}^G \\ 0 \\ \overline{Z}_{7 2}^D \\ \overline{Z}_{8 2}^D \\ \overline{Z}_{9 2}^D \\ 0 \end{bmatrix} \quad C_3 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \overline{Z}_{6 3}^G \\ \overline{Z}_{7 3}^D \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C_4 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \overline{Z}_{7 4}^D \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where:

- $C_1^G + C_1^D = C_1$ - column vector of the consumption of energy carriers concerning office rooms,
- $C_2^G + C_2^D = C_2$ - column vector of the consumption of energy carriers concerning auxiliary rooms,
- $C_3^G + C_3^D = C_3$ - column vector of the consumption of energy carriers concerning garages,
- $C_4^D = C_4$ - column vector of the consumption of energy carriers concerning standard equipment of the building.

The balance of all considered energy carriers in the building may be expressed by the following set of equations:

$$\begin{aligned}
G_1 &= a_{15}^G G_5 + \bar{Z}_{11}^G \\
G_2 &= a_{25}^G G_5 + \bar{Z}_{22}^G \\
G_3 &= \bar{Z}_{32}^G \\
G_4 &= \bar{Z}_{41}^G \\
G_5 &= \bar{Z}_{51}^G + \bar{Z}_{52}^G \\
G_6 &= \bar{Z}_{63}^G \\
D_7 &= a_{71}^D G_1 + a_{72}^D G_2 + a_{73}^D G_3 + a_{74}^D G_4 + a_{75}^D G_5 + a_{76}^D G_6 + \bar{Z}_{71}^D + \bar{Z}_{72}^D + \bar{Z}_{73}^D + \bar{Z}_{74}^D \\
D_8 &= a_{83}^D G_3 + \bar{Z}_{83}^D \\
D_9 &= \bar{Z}_{92}^D \\
D_{10} &= a_{102}^D G_2 + a_{103}^D G_3 + a_{104}^D G_4
\end{aligned} \tag{7.5}$$

Generally, the set of equations concerning the investigated complex building has the form:

$$\bigwedge_{i=1}^n : G_i + D_{Gi} = \sum_{j=1}^6 a_{ij}^G G_j + \bar{Z}_{i1}^G + \bar{Z}_{i2}^G + \bar{Z}_{i3}^G \tag{7.6}$$

$$\bigwedge_{i=n+1}^m : D_{Di} = \sum_{j=1}^6 a_{ij}^D G_j + \bar{Z}_{i1}^D + \bar{Z}_{i2}^D + \bar{Z}_{i3}^D + \bar{Z}_{i4}^D \tag{7.7}$$

Based on the designed data of the building the annual consumption of the internal energy carriers has been calculated. The results are as follows:

non-zero elements of the vector C1:

$\bar{Z}_{11}^G = 1058.58 \text{ GJ} = 294.05 \text{ MWh}$	- annual cooling consumption by all fan coil units,
$\bar{Z}_{41}^G = 1677.11 \text{ GJ} = 465.86 \text{ MWh}$	- annual heat consumption in the offices,
$\bar{Z}_{51}^G = 45544.8 \text{ Mg}$	- annual consumption of air from the air-conditioning unit in the offices,
$\bar{Z}_{71}^D = 2639.22 \text{ GJ} = 733.12 \text{ MWh}$	- annual consumption of electricity in the offices.

non-zero elements of the vector C2:

$\bar{Z}_{22}^G = 851.8 \text{ GJ} = 236.61 \text{ MWh}$	- annual (seasonal) heat consumption in auxiliary rooms,
$\bar{Z}_{32}^G = 994.6 \text{ Mg}$	- annual consumption of hot tap water,
$\bar{Z}_{52}^G = 30363.2 \text{ Mg}$	- annual air consumption in auxiliary rooms,
$\bar{Z}_{72}^D = 79.22 \text{ GJ} = 22.0 \text{ MWh}$	- annual consumption of electricity in auxiliary rooms,
$\bar{Z}_{82}^D = 10085 \text{ Mg}$	- annual consumption of drinking water,

$\bar{Z}_{92}^D = 576 \text{ GJ} = 160 \text{ MWh}$ - annual consumption of natural gas for catering.

non-zero elements of the vector C3:

$\bar{Z}_{63}^G = 435591 \text{ Mg}$ - annual amount of air for ventilating the garages,
 $\bar{Z}_{73}^D = 397.33 \text{ GJ} = 110.37 \text{ MWh}$ - annual consumption of electricity in the garages.

vector C4 includes only one non-zero element:

$\bar{Z}_{74}^D = 246.7 \text{ GJ} = 68.53 \text{ MWh}$ - annual consumption of electricity by the standard equipment of the building.

Non-zero elements of the consumption of energy carriers in the energy branches:

$Z_{15}^G = 69.78 \text{ GJ} = 19.38 \text{ MWh}$ - annual cooling consumption by the air conditioning unit,
 $Z_{25}^G = 975.9 \text{ GJ} = 271.08 \text{ MWh}$ - annual heat consumption by the air conditioning unit (heat demand for ventilation),
 $Z_{71}^D = 548.2 \text{ GJ} = 152.28 \text{ MWh}$ - annual consumption of electricity for the production of the cooling medium,
 $Z_{72}^D = 44.1 \text{ GJ} = 12.25 \text{ MWh}$ - annual consumption of electricity for the production of hot process water 85/55 °C,
 $Z_{73}^D = 3.62 \text{ GJ} = 1.01 \text{ MWh}$ - annual consumption of electricity for the production of hot tap water,
 $Z_{74}^D = 7.88 \text{ GJ} = 2.19 \text{ MWh}$ - annual consumption of electricity in the installation producing process water for the fan-coil units 60/45 °C,
 $Z_{75}^D = 269.9 \text{ GJ} = 74.97 \text{ MWh}$ - annual consumption of electricity for the ventilation of offices and auxiliary rooms,
 $Z_{71}^D = 387.89 \text{ GJ} = 107.75 \text{ MWh}$ - annual consumption of electricity for the mechanical extract ventilation of garages,
 $Z_{83}^D = 994.6 \text{ Mg}$ - annual consumption of drinking water for the production of hot tap water,
 $Z_{102}^D = 1827.66 \text{ GJ} = 507.68 \text{ MWh}$ - annual consumption of heat from the heating plant for the production of hot process water 85/55 °C,
 $Z_{103}^D = 170.53 \text{ GJ} = 47.37 \text{ MWh}$ - annual consumption of heat from the heating plant for the production of hot tap water,
 $Z_{104}^D = 1677.11 \text{ GJ} = 465.86 \text{ MWh}$ - annual consumption of heat from the heating plant for the production of hot process water 60/45 °C.

Table 7.2 presents the matrix **A** of the coefficients of consumption of energy carriers in an energy subsystem. The dimensions of the coefficients of matrix **A** result from the units for the particular energy carriers. For example, the coefficient a_{25} concerning the consumption of hot process water (85/55 °C) for the production of air from the air-conditioning unit is expressed by GJ/Mg. Table 7.3 presents the values of the consumption of energy carriers in the subsystem of consumers. Table 7.4 contains the results of the energy balance of the case-study complex building.

Table 7.2 Matrix of the coefficients a_{ij} of the consumption of energy carriers in all energy branches

	Energy carrier	1	2	3	4	5	6	7	8	9	10
1	Cooling medium (water- glycol) 6/12°C	0	0	0	0	0.000919	0	0	0	0	0
2	Hot process water 85/55 °C	0	0	0	0	0.01286	0	0	0	0	0
3	Hot tap water	0	0	0	0	0	0	0	0	0	0
4	Hot process water (fan coil) 60/45 °C	0	0	0	0	0	0	0	0	0	0
5	Air from conditioning unit	0	0	0	0	0	0	0	0	0	0
6	Ventilation air for garages	0	0	0	0	0	0	0	0	0	0
7	Electricity	0.4576	0.02413	0.00364	0.004699	0.003556	0.000890	0	0	0	0
8	Drinking water	0	0	1	0	0	0	0	0	0	0
9	Network natural gas	0	0	0	0	0	0	0	0	0	0
10	Heat from heat plant	0	1	0.1715	1	0	0	0	0	0	0

Table 7.3 Vectors of the values of the annual consumption of energy carriers $\bar{Z}_{ik}$ in the subsystem of consumers

Technological consumers						
	Energy carrier	Unit	Office rooms	Auxiliary rooms	Garages	Standard equipment of building
1	Cooling medium (water- glycol) 6/12°C	GJ	1059	0	0	0
2	Hot process water 85/55 °C	GJ	0	851.8	0	0
3	Hot tap water	t	0	994.6	0	0
4	Hot process water (fan coil) 60/45 °C	GJ	1677.11	0	0	0
5	Air from conditioning unit	t	45544.8	30363.2	0	0
6	Ventilation air for garages	t	0	0	435591	0
7	Electricity	GJ	2639.22	79.22	397.33	246.7
8	Drinking water	t	0	10085	0	0
9	Network natural gas	GJ	0	576	0	0
10	Heat from heat plant	GJ	0	0	0	0

Table 7.4 Vectors of the values of the annual production G_i and external supply D_i of energy carriers

	Energy carrier	Unit	Production G	Supply D
1	Cooling medium (water- glycol) 6/12°C	GJ	1128	0
2	Hot process water 85/55 °C	GJ	1828	0
3	Hot tap water	t	994,6	0
4	Hot process water (fan coil) 60/45 °C	GJ	1677	0
5	Air from conditioning unit	t	75908	0
6	Ventilation air for garages	t	435591	0
7	Electricity	GJ	0	4608
8	Drinking water	t	0	11080
9	Network natural gas	GJ	0	576
10	Heat from heat plant	GJ	0	3675

7.3. Analysis of cumulative energy consumption

The analysis is based on the results of the balance of direct energy consumption in the complex building under consideration. Input data for the determination of the indices of cumulative energy consumption in complex buildings are also indices of cumulative energy consumption concerning the energy carriers supplied to the buildings from outside. This approach is justified because the energy management of complex buildings is connected unilaterally with the energy system of the whole country as a result of providing energy carriers to these buildings.

The analysis of the direct consumption of energy in a building is not yet complete, because the final energy carriers used directly are produced in the larger network of technological and energy processes and transported, also using energy. As mentioned in section 6.2 the index of cumulative energy consumption may be calculated separately for various forms of energy (final or primary), just as the global index describing the overall consumption of various forms of primary energy can be so calculated. Further on in this book, the latter definition of cumulative energy consumption will be applied.

The input data for the procedure of calculating the coefficients of cumulative energy consumption in complex buildings result from the energy balance of the buildings and

coefficients of cumulative energy consumption of energy carriers supplied to the buildings. In the case under analysis the following indices of cumulative energy consumption, concerning the supply from outside, have been taken into account [3, 5, 6]:

electricity:	$e_7^* = 3.83 \text{ GJ/ GJ,}$
drinking water:	$e_8^* = 0.03122 \text{ GJ/Mg,}$
natural gas:	$e_9^* = 1.03 \text{ GJ/ GJ,}$
heat from the district heating system:	$e_{10}^* = 1.23 \text{ GJ/ GJ.}$

In the case of the investigated building the set of equations of the balance of cumulative energy consumption may be expressed as follows:

$$\begin{aligned}
 a_{7\ 1} \cdot e_7^* &= e_1^* \\
 a_{7\ 2} \cdot e_7^* + a_{10\ 2} \cdot e_{10}^* &= e_2^* \\
 a_{7\ 3} \cdot e_7^* + a_{8\ 3} \cdot e_8^* + a_{10\ 3} \cdot e_{10}^* &= e_3^* \\
 a_{7\ 4} \cdot e_7^* + a_{10\ 4} \cdot e_{10}^* &= e_4^* \\
 a_{1\ 5} \cdot e_1^* + a_{2\ 5} \cdot e_2^* + a_{7\ 5} \cdot e_7^* &= e_5^* \\
 a_{7\ 6} \cdot e_7^* &= e_6^*
 \end{aligned} \tag{7.8}$$

Table 7.5 shows the results of calculations of the indices of cumulative energy consumption concerning all energy carriers in the analysed building. Fig. 7.2 and Table 7.6 illustrates the annual cumulative energy consumption concerning the individual consumers of energy carriers in the building (offices, auxiliary rooms, garages, and standard equipment of the building). Fig. 7.3. presents the annual shares of cumulative energy consumption concerning energy carriers supplied from outside.

Table 7.5. Indices of cumulative energy consumption concerning all energy carriers

No	Energy carrier	Unit	Coefficient of cumulative energy consumption
1	Cooling medium 6/12 ° C	GJ/GJ	1,753
2	Hot process water 85/45 ° C	GJ/GJ	1,322
3	Hot tap water	GJ/t	0,2561
4	Hot process water 60/45 ° C	GJ/GJ	1,248
5	Air from the air conditioning unit	GJ/t	0,03224
6	Ventilation air for garages	GJ/t	0,003409

Table.7.6. Annual cumulative energy consumption (GJ/year) burdening the consumer subsystem

No	Energy carrier	Office rooms	Auxiliary rooms	Garages	Monitoring and control
1	Cooling medium 6/12 °C	1855,691	0	0	0
2	Hot process water 85/45 °C	0	1126,08	0	0
3	Hot tap water	0	254,7171	0	0
4	Hot process water 60/45 °C	2093,033	0	0	0
5	Air from the air conditioning unit	1468,364	978,9096	0	0
6	Ventilation air for garages	0	0	1484,93	0
7	Electricity	10108,21	303,4126	1521,774	944,861
8	Drinking water	0	314,8537	0	0
9	Natural gas	0	593,28	0	0
10	Heat from heating plant	0	0	0	0
	Overall	15525,3	3571,253	3006,704	944,861

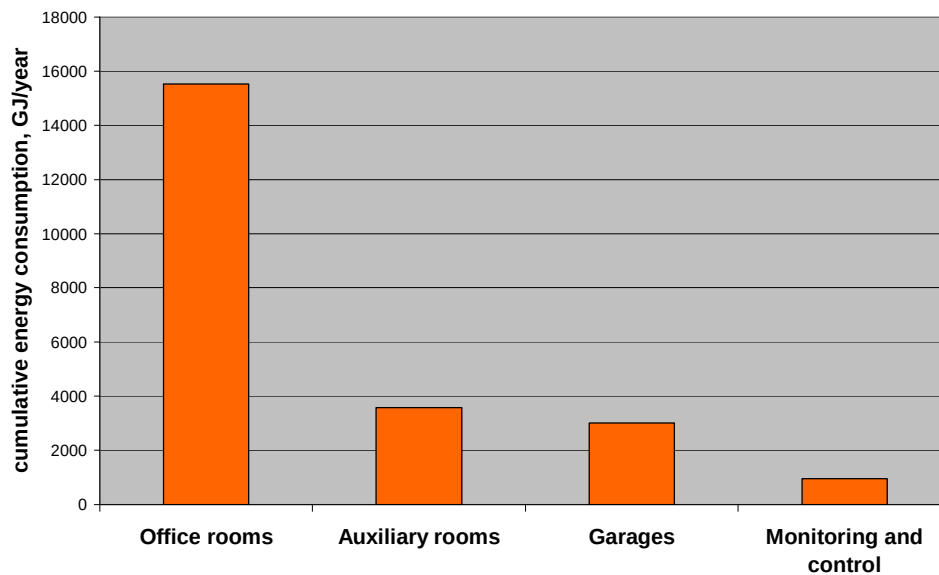


Fig. 7.2. Annual cumulative energy consumption concerning the individual consumers of energy carriers in the building

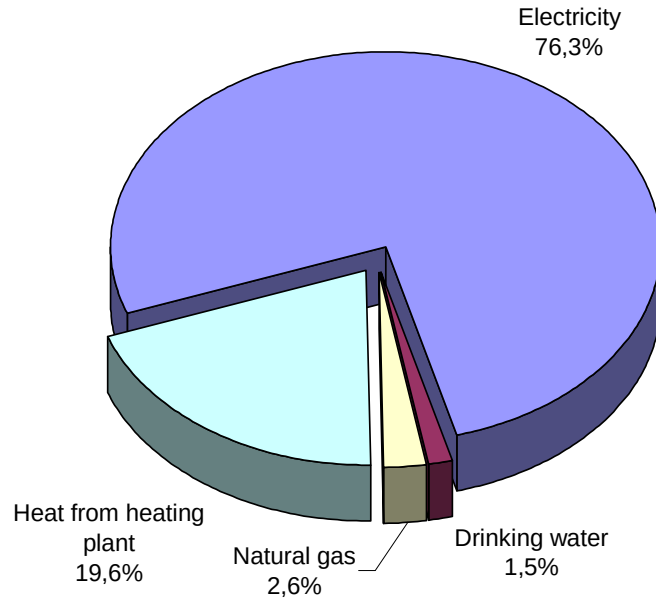


Fig. 7.3. Annual shares of cumulative energy consumption concerning energy carriers which are supplied to the considered office building from outside

Using the results of the annual balance of energy carriers supplied to the case-study building from outside we can calculate the annual cumulative energy consumption of primary energy.

$$E^* = \sum_{i=7}^{10} D_i e_i^* \quad (7.9)$$

In the case under consideration the annual cumulative energy consumption is $E^* = 23047,66$ GJ. With respect to the floor area of the offices (8000m^2) the calculated index of cumulative energy consumption amounts to $e^* = 2.881$ GJ/(a m^2).

7.4. Analysis of cumulative emissions of noxious substances

In the example of calculations being analysed, the emission of NO_x and CO₂ compounds have been considered. The input data for this procedure result from the annual balance of the direct consumption of energy in the complex building being analysed [3]. The indices of cumulated emissions charging the energy carriers supplied to the complex building from outside, as well as the quantity of direct emissions, result from energy and technological processes.

For the purpose of the presented analysis the indices of cumulative NO_x and CO₂ emissions have been determined concerning energy carriers supplied from outside (Table 7.7) [1]. Based on process analysis, the indices of direct emissions in the energy branches of

complex buildings have been determined. Direct emissions connected with natural gas occur only in auxiliary rooms in the course of catering services.

Table 7.7. Input data for the analysis of cumulative emissions in the analysed building

Energy carrier	Coefficient of the cumulative NOx emission	Coefficient of the cumulative CO2 emission
Electricity	$s_{NOx\ 7}^* = 0,4861 \text{ kg/GJ}_{el}$	$s_{CO2\ 7}^* = 257,71 \text{ kg/GJ}_{el}$
Drinking water	$s_{NOx\ 8}^* = 0,003936 \text{ kg/Mg}$	$s_{CO2\ 8}^* = 1,66 \text{ kg/Mg}$
Natural gas ⁽¹⁾	$s_{NOx\ 9}^* = 0,004726 \text{ kg/GJ}_{ch}$	$s_{CO2\ 9}^* = 54,82 \text{ kg/GJ}_{ch}$
Heat from heating plant	$s_{NOx\ 10}^* = 0,2001 \text{ kg/GJ}_{th}$	$s_{CO2\ 10}^* = 106,11 \text{ kg/GJ}_{th}$
⁽¹⁾ includes also direct emissions		

Table.7.8. Coefficients of NOx cumulative emissions concerning each energy carrier considered in the analysis

No	Energy carrier	Unit	NOx	CO2
1	Cooling medium 6/12 °C	kg/GJ	0,2224	117,9
2	Hot process water 85/45 °C	kg/GJ	0,2118	112,3
3	Hot tap water	kg/Mg	0,04002	20,8
4	Hot process water 60/45 °C	kg/GJ	0,2024	107,3
5	Air from the air conditioning unit	kg/Mg	0,004657	2,469
6	Ventilation air	kg/Mg	0,0004326	0,2294

Table.7.9. Annual cumulative emissions generated by the consumer subsystem (kg NOx/CO2/year)

No	Energy carrier	Office rooms		Auxiliary rooms		Garages		Monitoring and control	
		NOx	CO2	NOx	CO2	NOx	CO2	NOx	CO2
1	Cooling medium 6/12 °C	235,4282	124806,6	0	0	0	0	0	0
2	Hot process water 85/45 °C	0	0	180,4112	95657,14	0	0	0	0
3	Hot tap water	0	0	39,80389	20687,68	0	0	0	0
4	Hot process water 60/45 °C	339,4471	179953,9	0	0	0	0	0	0
5	Air from the air-conditioning unit	212,1021	112450,1	141,4014	74966,74	0	0	0	0
6	Ventilation air	0	0	0	0	188,4367	99924,58	0	0
7	Electricity	1282,925	680153,4	38,50884	20415,79	193,1421	102395,9	119,9209	63577,06
8	Drinking water	0	0	39,69456	16741,1	0	0	0	0
9	Natural gas	0	0	2,722176	31576,32	0	0	0	0
10	Heat from heating plant	0	0	0	0	0	0	0	0
	Overall	2069,902	1097364	442,5421	260044,8	381,5788	202320,5	119,9209	63577,06

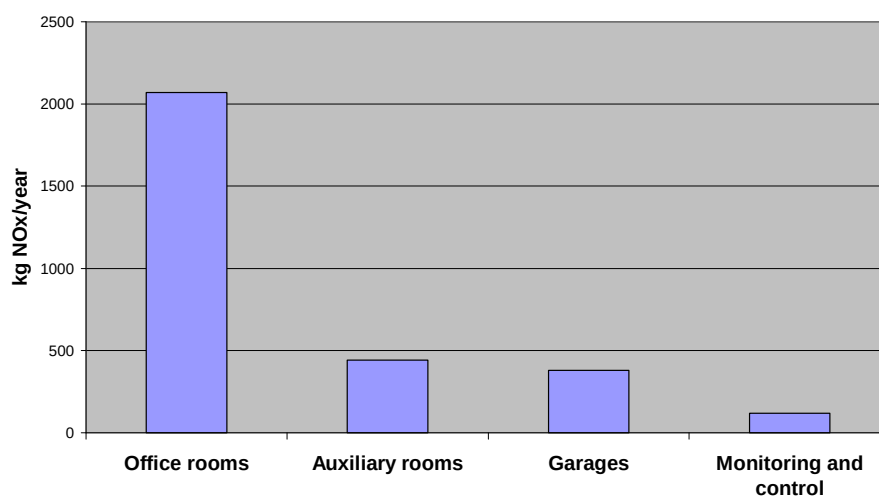


Fig. 7.4. Annual NOx cumulative emissions generated by the consumer subsystem of the office building under consideration

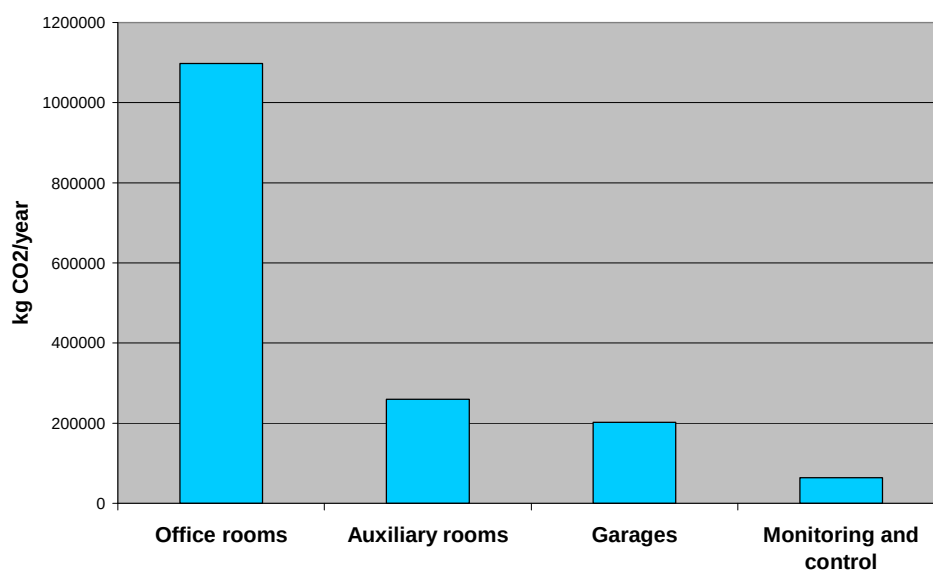


Fig. 7.5. Annual CO2 cumulative emissions generated by the consumer subsystem of the office building under consideration

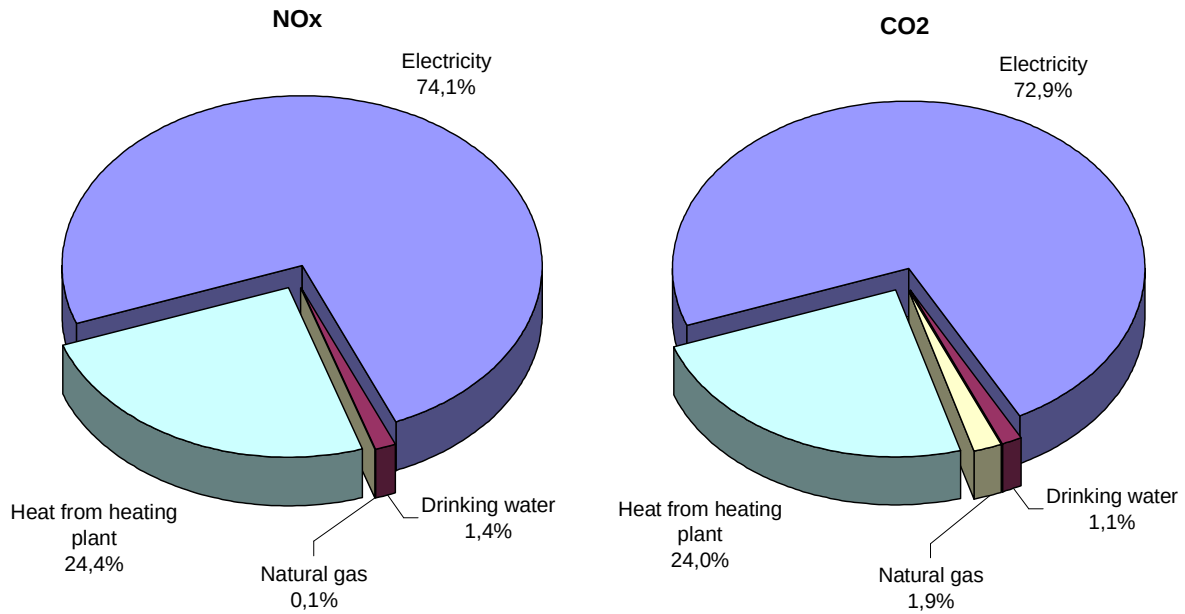


Fig. 7.6. Shares of NOx and CO2 cumulative emissions connected with energy carriers supplied to the office building under consideration

Studies have shown that on the basis of the annual energy balance a mathematical model of the balance of cumulative emissions for a complex building can be formulated, and the coefficients of cumulative emissions concerning all energy carriers in the building can be calculated. In the example above, this approach has been used to analyse cumulative NOx and CO2 emissions generated by an exemplary office building. The analysis of this building has shown that the most cumulative emissions result from the demand for electricity (Fig 7.7, Table 7.8). Office rooms with an air-conditioning system, fan-coil units, equipment and controls are the main electricity consumers in the building under analysis and are responsible for most cumulative NOx and CO2 emissions (70 per cent) (Fig. 7.4-5, Table 7.9). The energy consumption in offices can be potentially improved; for example, by applying low-energy cooling methods.

The annual cumulative NOx and CO2 emissions amount to $S_{NOx}^* = 3014 \text{ kg/a}$, $S_{CO2}^* = 1623,4 \text{ Mg/a}$. With respect to the floor area of the offices (8000 m^2) the calculated indices of cumulative emissions amount to $s_{NOx}^* = 0,3768 \text{ kg/(a m}^2\text{)}$ and $s_{CO2}^* = 202,93 \text{ kg/(a m}^2\text{)}$.

7.5. Thermo-ecological cost calculations

The mathematical model of the balance of thermo-ecological costs described in Chapter 6 was applied to analyse a case-study complex building. The input data for the procedure of

calculating the indices of thermo-ecological costs in complex buildings result from the energy balance of the building and indices of thermo-ecological costs of the energy carriers supplied to the building. This approach is justified, as it is in the analysis of cumulated energy consumption, because the energy management of the complex building is connected with the energy system of the country merely by the supply of energy carriers from this larger system to the complex building [2]. There are no strong reverse connections. In the analysed case, the following indices of thermo-ecological costs concerning the supply from outside have been taken into account [2, 5]:

electricity: 3.6 MJ/MJ_{el},

drinking water: 0,02915 GJ/t,

natural gas: 714.8 MJ/kmol.

The index of thermo-ecological costs of heat production in the district heating plant has been calculated based on the input-output balance equation of thermo-ecological costs. Only heat produced in the coal-fired district heating plant has been taken into consideration. The average specific consumption of coal in a district heating plant is determined basing on the thermal efficiency of the heating plant. In the analysed case the thermal efficiency was assumed to amount to $\eta_{EH}=0.8$. The following coefficients have been taken into account:

- emissions of harmful substances: $p_{SO_2 H}=0.0008125$; $p_{NO_x H}=0.0000375$; $p_{d H}=0.00175$ (dust) kg/MJ_H,
- coefficient of the consumption of coal for the production of heat in the district heating plant: $a_{C H}=0.05435$ kg/MJ_H,
- index of the thermo-ecological cost of the production and delivery of coal: $\rho_C=27.2$ MJ/MJ.

The index of the thermo-ecological cost of the production of heat in the district heating plant may be expressed as:

$$\rho_H = a_{C H} \rho_C + \sum_h p_{h H} \zeta_h \quad (7.10)$$

The balance equation (Eq. 7.10) has been presented in Fig. 7.7.

The indices describing the cumulative exergy consumption of non-renewable resources due to the emissions of harmful substances [2, 5] are:

$$\zeta_{SO_2} = 49.3 \text{ MJ / kg } SO_2$$

$$\zeta_{NO_x} = 49.3 \text{ MJ} / \text{kg } NO_x$$

$$\zeta_d = 10.19 \text{ MJ} / \text{kg dust}$$

The index of the thermo-ecological cost of heat production in the district heating system:

$$\rho_H = 1.538 \text{ MJ/MJ}_H$$

Efficiency of heat delivery to the building:

$$\eta_{HT} = 0.85$$

Thermo-ecological cost of heat supplied to the building:

$$\rho_{IO} = 1.8 \text{ MJ/MJ}_H$$

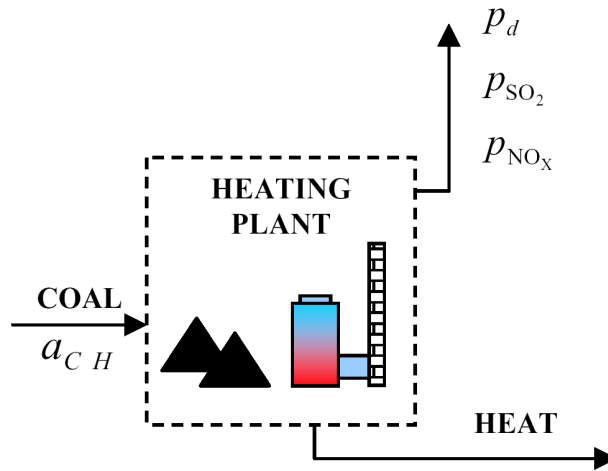


Fig. 7.7. Structure of the balance equation concerning the thermo-ecological cost of the production of heat

No combustion processes are considered in the energy subsystem of the building. The natural gas is consumed only for catering in auxiliary rooms (subsystem of consumers). In the energy subsystem of the building the production of all energy carriers does not involve emissions of waste products $\sum_K p_{hj} \zeta_h$.

For this building the set of balance equation of cumulative energy consumption concerning production of energy carriers has the following form:

$$\rho_1 = a_{7\ 1}^D \cdot \rho_7 \quad (7.11)$$

$$\rho_2 = a_{7\ 2}^D \cdot \rho_7 + a_{10\ 2}^D \cdot \rho_{10}$$

$$\rho_3 = a_{7\ 3}^D \cdot \rho_7 + a_{8\ 3}^D \cdot \rho_8 + a_{10\ 3}^D \cdot \rho_{10}$$

$$\rho_4 = a_{7\ 4}^D \cdot \rho_7 + a_{10\ 4}^D \cdot \rho_{10}$$

$$\rho_5 = a_{1\ 5}^G \cdot \rho_1 + a_{2\ 5}^G \cdot \rho_2 + a_{7\ 5}^D \cdot \rho_7$$

$$\rho_6 = a_{7\ 6}^D \cdot \rho_7$$

Fig. 7.8 shows an example of the balance equation of the thermo-ecological cost in one energy branch in the building (air-conditioning unit, $j=5$). Table 7.10 shows the results of calculations of the indices of the thermo-ecological cost of energy carriers in the complex building.

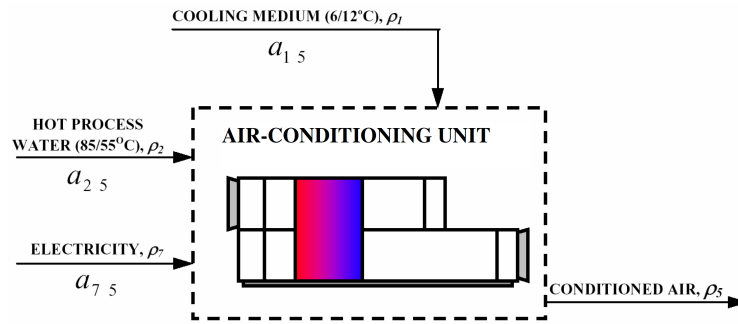


Fig. 7.8. Exemplary balance of the thermo-ecological cost in one energy branch ($j=5$)

Using the results of the balance of the thermo-ecological cost in the energy subsystem, the annual thermo-ecological cost concerning the subsystem consumers in the building (office rooms, auxiliary rooms, garages and standard equipment) can be calculated (Figure 7.11, Table 7.11). Shares of non-renewable exergy consumption connected with energy carriers supplied to the case-study building are presents Fig. 7.9. For this analysis the additional thermo-ecological costs of the waste products of combusting natural gas in auxiliary rooms (subsystem of consumers) have been taken into account.

In these calculations the following coefficient for natural gas has been considered: $p_{\text{NOx 9}}=0.00003$.

Table 7.10. Results of calculations concerning the thermo-ecological costs of energy carriers

No	Energy carrier	Unit	Thermo-ecological cost
1	Cooling medium 6/12 °C	GJ/GJ	1,647

2	Hot process water 85/45 °C	GJ/GJ	1,887
3	Hot tap water	GJ/Mg	0,351
4	Hot process water 60/45 °C	GJ/GJ	1,817
5	Air from the air-conditioning unit	GJ/Mg	0,03858
6	Ventilation air for garages	GJ/Mg	0,003204

Table 7.11. Results of calculations – annual thermo-ecological costs concerning the subsystem of consumers

No	Energy carrier	Office rooms	Auxiliary rooms	Garages	Monitoring and control
1	Cooling medium 6/12 °C	1743,481	0	0	0
2	Hot process water 85/45 °C	0	1607,347	0	0
3	Hot tap water	0	349,1046	0	0
4	Hot process water 60/45 °C	3047,309	0	0	0
5	Air from the air-conditioning unit	1757,118	1171,412	0	0
6	Ventilation air for garages	0	0	1395,634	0
7	Electricity	9501,192	285,192	1430,388	888,12
8	Drinking water	0	293,9778	0	0
9	Natural gas	0	513,1584	0	0
10	Heat from the heating plant	0	0	0	0
	Overall	16049,1	4220,192	2826,022	888,12

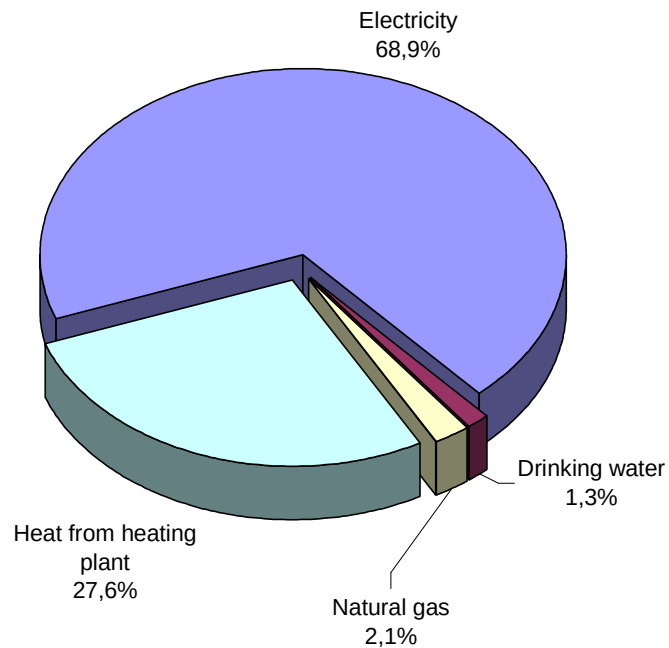


Fig. 7.9. Shares of non-renewable exergy consumption connected with energy carriers supplied to the case-study office building

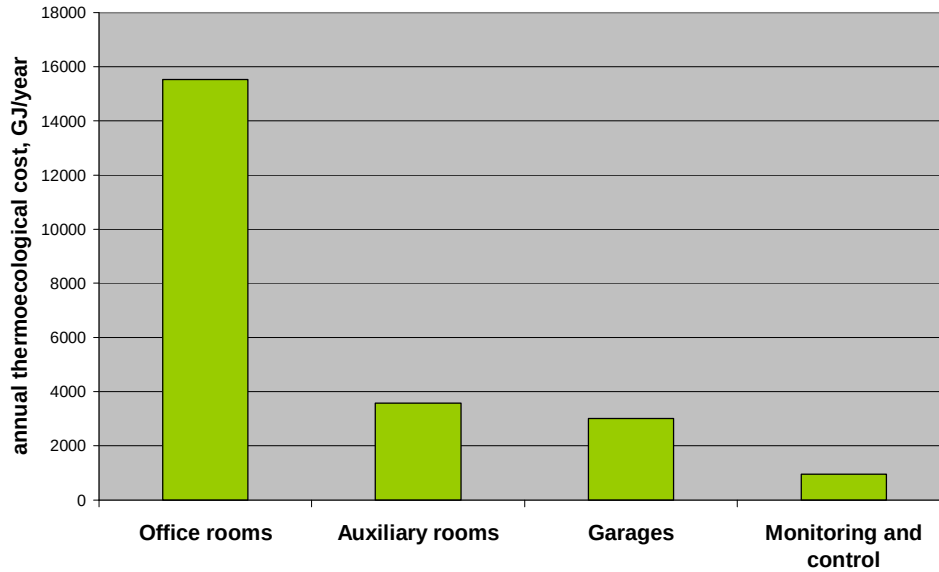


Fig. 7.10. Annual thermo-ecological cost concerning the subsystem of consumers in the analysed building

The analysis of an exemplary building has shown that the most non-renewable exergy consumption results from the demand for electricity in the building. Office rooms (with an air-conditioning system, fan-coil units, equipment and controls) dominate in the electricity consumption in the analysed building, and they are responsible for most non-renewable exergy consumption.

The annual thermo-ecological cost (non-renewable exergy consumption) amounts to $E^* = 23983,57$ GJ. With respect to the floor area of the offices (8000m^2) the calculated index of thermo-ecological cumulative energy consumption amounts to $e^* = 2,10$ GJ/(a m^2).

7.6. Example of systems approach to the analysis of the application of night-cooling ventilation in complex buildings ¹

7.6.1. Night-cooling ventilation strategy

Before mechanical cooling systems were developed, people used natural ways for cooling, such as allowing natural draughts through cooled spaces, pouring and spraying water on hot surfaces inside a building, and constructing massive partitions to absorb sun radiation. Such methods were improved over centuries and have become a part of building constructions. Today, even though mechanical cooling systems are available, low-energy cooling techniques modelled on past experiences are still in use and in progress. In some cases low-energy

¹ This example was elaborated during K. Hoinka's stay at Brunel University under the supervision of Dr. Maria Kolokotroni.

cooling techniques compete with traditional mechanical cooling systems (e.g. compressor or absorption refrigeration units). By applying low-energy cooling methods in complex buildings, we can reduce energy demands, the size of energy devices, and even eliminate mechanical cooling systems. One of the available methods is natural or mechanical ventilation at night when the external air temperature is relatively low. This air exchange removes heat accumulated in the building structure during the day. In many buildings (e.g. office buildings) there are no occupants at night-time, so the air flow rate may be high. This allows an effective heat exchange between the outside air and the building structure. The technique may significantly increase the thermal comfort of the occupants and reduce the demand for cooling in complex buildings. It leads to better health for the occupants, a reduction of noxious emissions to the environment, and a reduction in primary energy consumption. Also, the investment cost of cooling installations may be reduced, or the traditional mechanical cooling system may even turn out to be unnecessary. The heavier the construction of the building, the better is the effect of night ventilation. There are four positive effects of night ventilation [4]:

- reduction in internal peak air temperature,
- reduction in air temperature throughout the day, and in particular during the morning hours,
- reduction in the temperature of the internal walls,
- creation of a time lag between external and internal temperature changes.

Fig. 7.11 shows a typical effect of night ventilation in an office building [2]. Positive effects of night ventilation on the energy balance of the building depend on many factors. One of them is the kind of the HVAC system applied in the building.

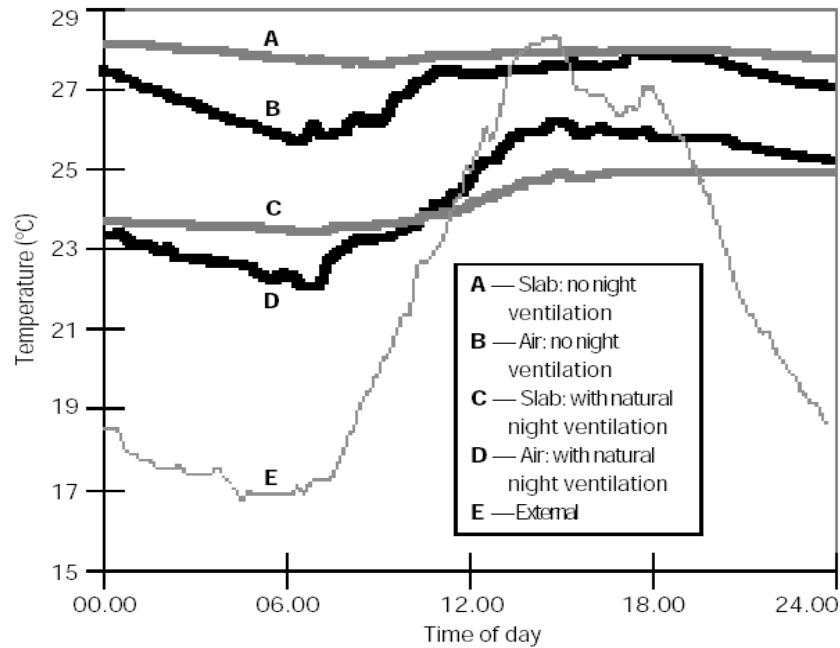


Fig. 7.11. Effect of night ventilation in an office building [2]

The energy savings achieved by applying night cooling ventilation depend strictly on the traditional cooling system which is used in the building. In complex buildings we can consider the following different cooling systems [2]:

Mechanical systems:

- mechanical ventilation by supply fans,
- mechanical ventilation by extract fans,
- mechanical ventilation balanced by supply and extract fans.

Natural ventilation systems:

- single-sided single opening,
- single-sided double opening,
- cross ventilation,
- stack ventilation.

Active cooling systems:

- fan-coil system,
- displacement ventilation system.

Control of night-cooling ventilation

During night ventilation the air flows throughout the building, and its rate should be automatically controlled. When mechanical night ventilation is applied, the fans regulate a proper airflow. In the case of natural ventilation the airflow is regulated by servo-mechanically controlled windows and other ventilation gaps. The airflow during the night should pre-cool the building as much as possible, but in the morning hours of the next day the temperature of the internal air and surfaces should not be too low, in order to ensure the thermal comfort of the occupants. Fig. 12 shows an example of a climate control system of night ventilation.

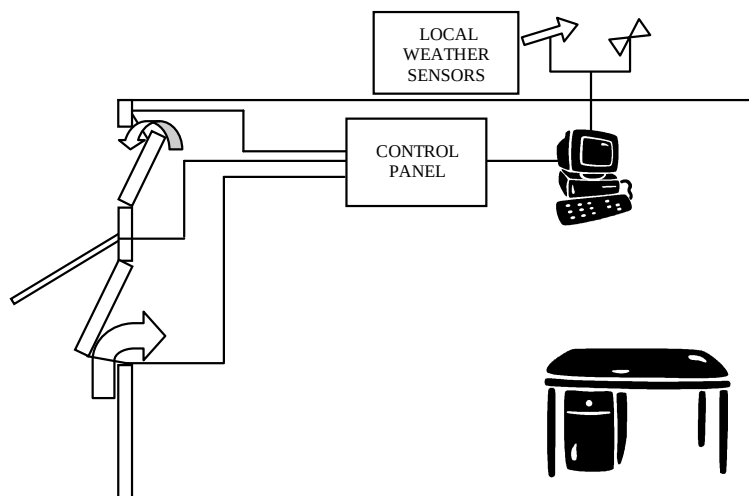


Fig. 7.12. Climate control system for night ventilation.

Example of an analysis of the application of night-cooling ventilation in an office building

This analysis concerns the application of night-cooling ventilation in the office building under consideration and estimates the potential energy savings and reduction in the capacity of the required units. This is achieved by using the thermal and air flow simulation program Nite Cool. Thermal analysis is based on BRE's (Building Research Establishment - UK) high-speed thermal simulation method 3TC. Nite Cool reads in parameter files for each building construction, and the analysis is restricted to a single office space, measuring 10m in length by 6m in depth by 3m in height.

The considered parameters which affect the driving forces for natural ventilation are:

- speed and direction of the wind
- temperature difference inside and outside the building

- opening areas of the window/ventilation gaps
- difference in height between the gaps or opening height of single openings.

Table 7.12 shows the main characteristics and input parameters which characterise the office building (on the basis of the project of this building) used in the calculations.

Tab. 7.12. The main input data for calculations by Nite Cool program

Input Parameters	Values
Internal gains	55W/m ²
Infiltration	0.5 ach “air changes per hour”
Building orientation	270°
Building weight	Medium
Glazing ratio	0.4
Occupied hours	08:00-18:00
Solar protection	0.7
Weather data	Min and max temperatures
Terrain	Urban
Building height	24m
Wind direction W	270°
Wind speed	Values from program weather data
Cps, faces of building	Inlet: 1, outlet: 2
Roof pitch	<11 dig
Running time of night ventilation system	24:00÷07:00am
Considered night cooling systems	• Mechanical supply ventilation • Mechanical extract ventilation • Mechanical balanced ventilation • Single-side single opening • Single-side double opening • Cross ventilation • Stack ventilation
Day cooling	Fan-coil air-conditioning
Set point	20°C
Fresh air delivered	5 ach
COP	3
Supply fan power	1 W/l/s –Best practice
Extract fan power	0.75 W/l/s – Best practice

The calculations concern each month separately. The daily maximum and minimum temperature was chosen from among real data of external temperature measured in Poland. Fig. 7.13 and 7.14 show curves (plotted using the Nite Cool program) of internal temperature and outside air temperature on one analysed day and over a week. The air-conditioning system selected for day-cooling is a 100% fresh-air fan-coil system with a COP of 3, with a

supply fan of 1 W/l/s specific power, while the extract fan has a specific power of 0.75 W/l/s; both values were selected to represent the best practice. A suitable control strategy is necessary for the most effective use of night ventilation. Overloading must also be avoided. In this case night ventilation is designed to run all night and be switched off at 7 a.m. by a timer. Night-cooling starts at 10 p.m. if the inside peak temperature during the previous day was higher than 20 °C. It continues all night when the inside temperature is higher than the outside temperature plus an offset of 2K. The effects of applying night ventilation have been investigated concerning all possible kinds of ventilation strategies and for each month of the cooling season (May, June, July, August, and September). The results of energy savings with reference to existing energy consumption for cooling the building are presented in Table 7.13 and on Fig. 7.15-21.

The study of the building has shown that using mechanical night ventilation is not useful and leads to increased energy consumption because of the operation of the fans, required (Fig. 7.19-21) especially when we consider balanced night ventilation (Fig. 7.21). The fans consume electricity and generate heat. The best solution for building is the application of stack or cross night ventilation. These systems provide most energy savings (Fig. 7.15 and 7.16). In further calculations cross ventilation has been analysed because, for this particular building construction, cross ventilation can be realised.

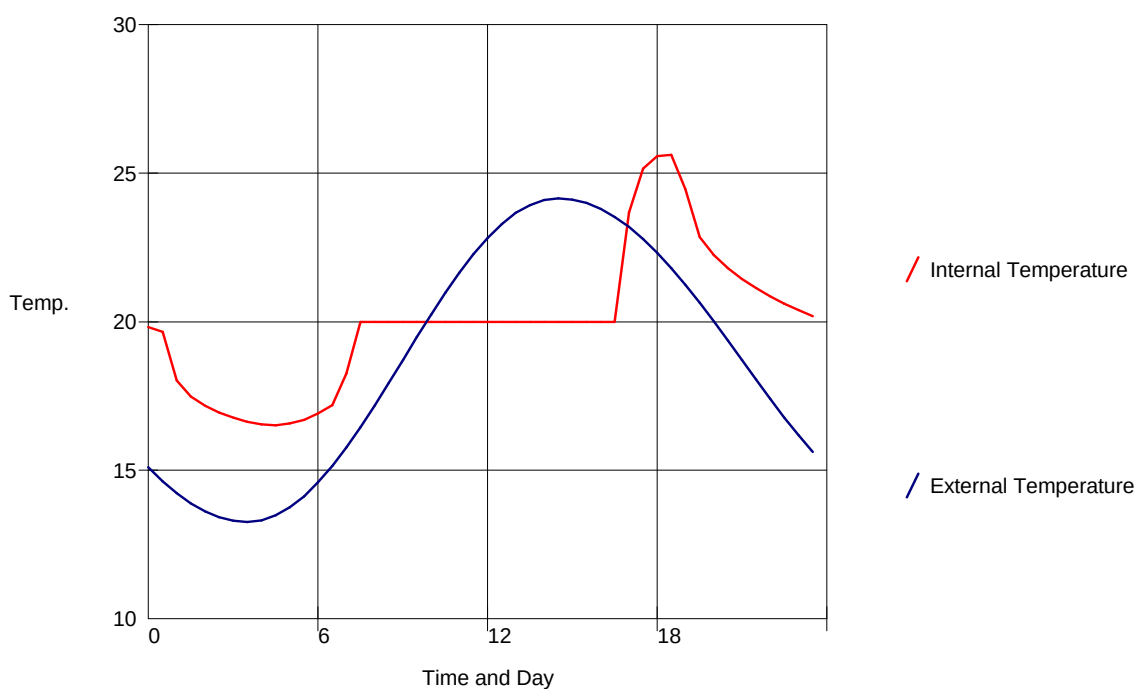


Fig. 7.13. Internal and external air temperature simulation for one analysed day

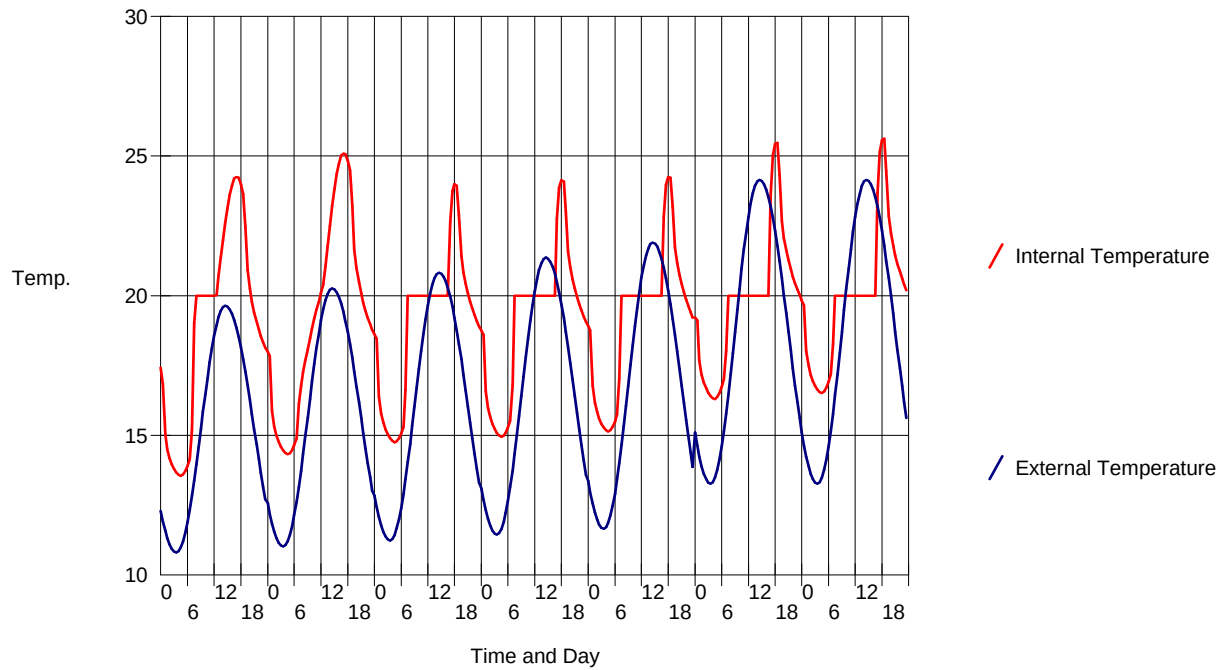


Fig. 7.14. Internal and external air temperatures for one analysed week

Tab. 7.13. Energy savings during the cooling season achieved by the night-cooling ventilation system in the analysed building

Type of night ventilation	Month					
	May	June	July	August	September	
Stack ventilation	6,72	5,61	4,04	3,82	4,6	Energy savings [%]
Cross ventilation	6,5	5,45	3,91	3,71	4,51	
Single-side double opening ventilation	4,68	3,83	2,72	2,53	2,85	
Single-side single opening ventilation	2,56	2,11	1,48	1,36	1,62	
Mechanical supply ventilation	-14,91	-13,52	-12,86	-14,53	-18,39	
Mechanical extract ventilation	-8,33	-7,71	-7,74	-8,99	-11,53	

Mechanical balanced ventilation	-31,28	-27,94	-25,55	-28,28	-35,41	

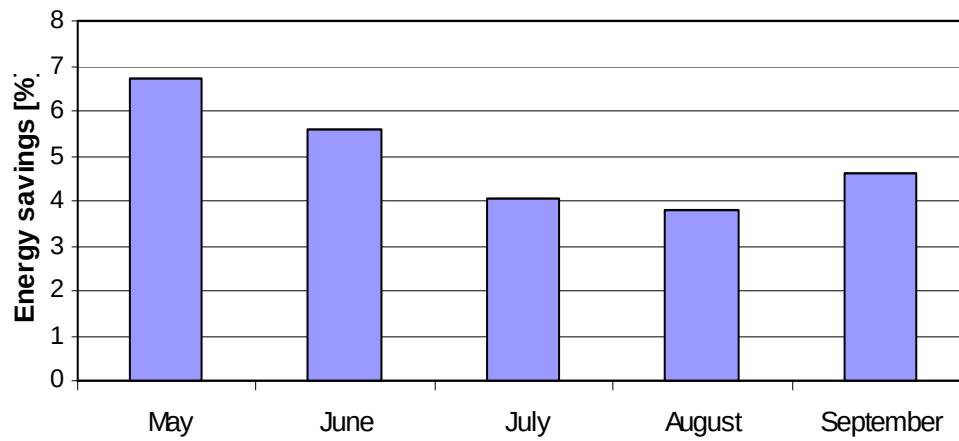


Fig. 7.15. Energy savings during the cooling season applying the stack night cooling ventilation system in case-study building

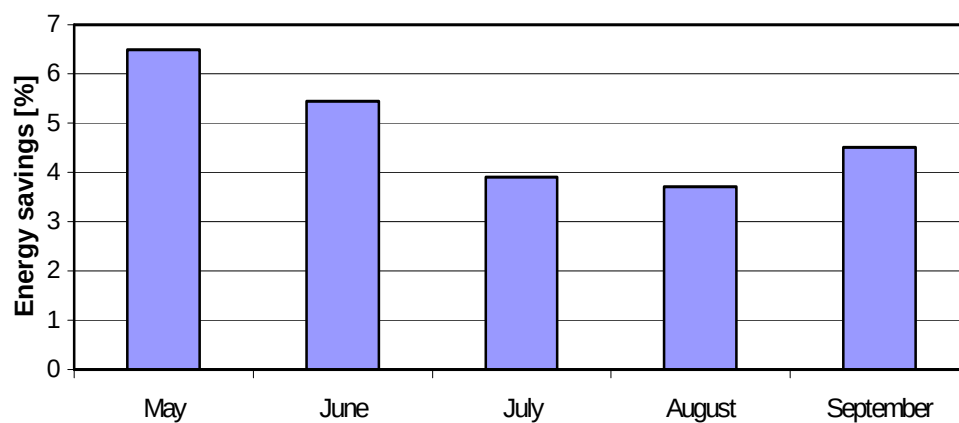


Fig. 7.16. Energy savings during the cooling season applying the cross night cooling ventilation system in case-study building

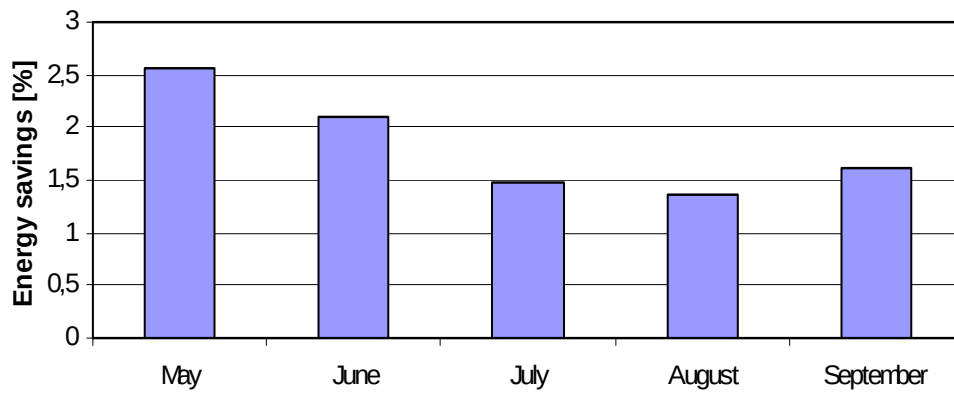


Fig. 7.17. Energy savings during the cooling season applying the single-side single opening night cooling ventilation system in case-study building

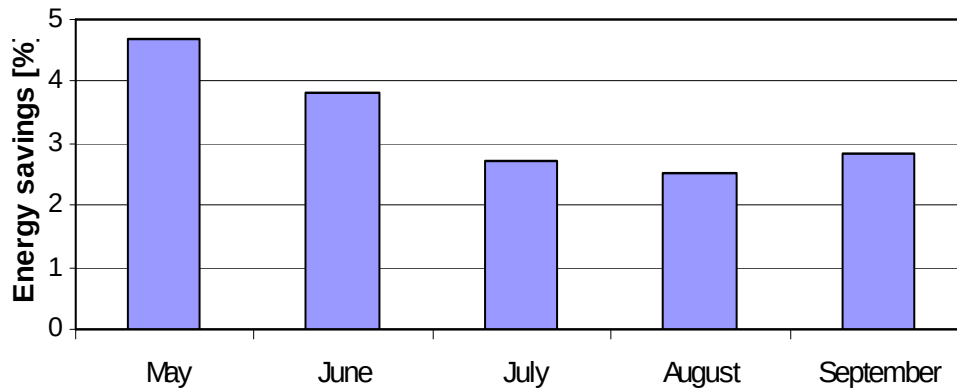


Fig. 7.18. Energy savings during the cooling season applying the single-side double opening night cooling ventilation system in case-study building

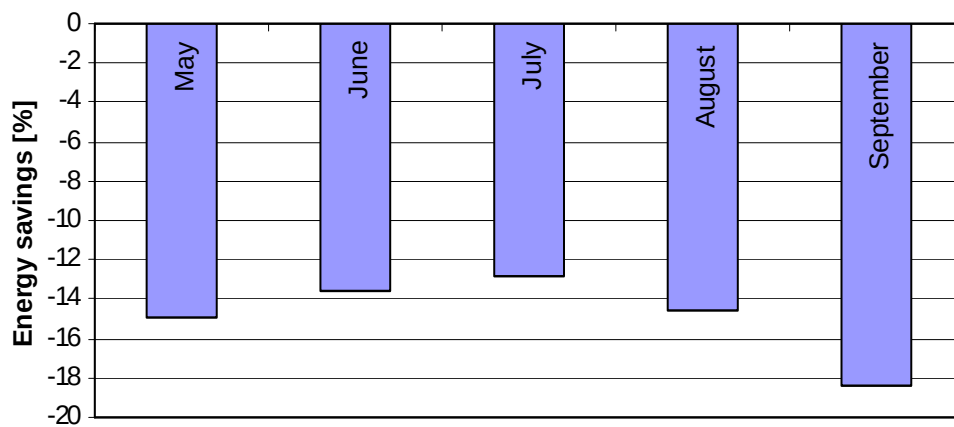


Fig. 7.19. Energy savings during the cooling season applying the mechanical-supply night cooling ventilation system in case-study building

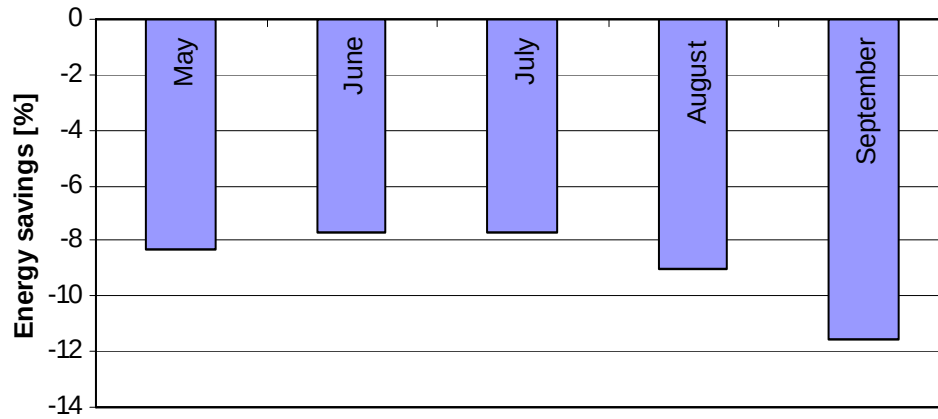


Fig. 7.20. Energy savings during the cooling season applying the mechanical-extract night cooling ventilation system in case-study building

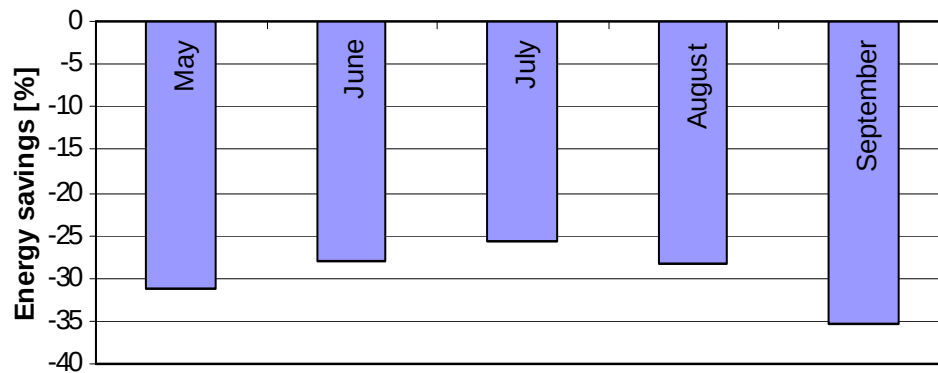


Fig. 7.21. Energy savings during the cooling season applying the mechanical-balanced night cooling ventilation system in case-study building

In the next stage of calculations cross ventilation has been analysed and optimised because this solution is most suitable for the construction of the building. Fig. 7.22 shows energy savings as a function of the duration of night ventilation when that strategy is applied. On the basis of this chart we can confirm that the longer the operation, the greater are the benefits. The study has shown that most energy savings are achieved when night ventilation operates from 8 p.m. to 7 a.m.

On the basis of calculations of the cooling demand for the case-study building without night ventilation (Fig. 7.23), and the results obtained by analysing the application of that system, the monthly consumption of electricity for cooling has been calculated. Fig. 7.24 shows a comparison of the seasonal consumption of electricity for the production of the cooling agent with and without night ventilation.

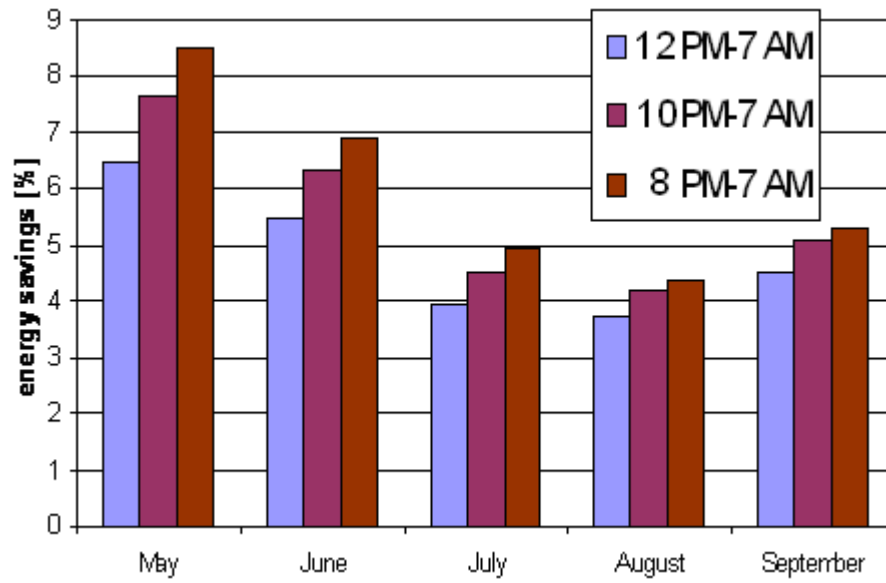


Fig. 7.22. Energy savings as a function of the running time of night cross ventilation

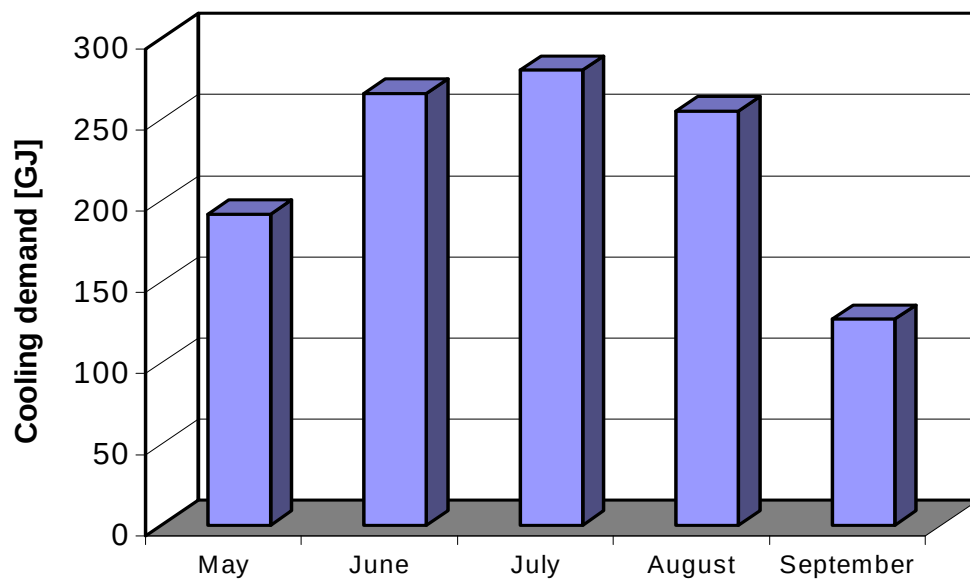


Fig. 7.23. Cooling demand for each month for case-study building

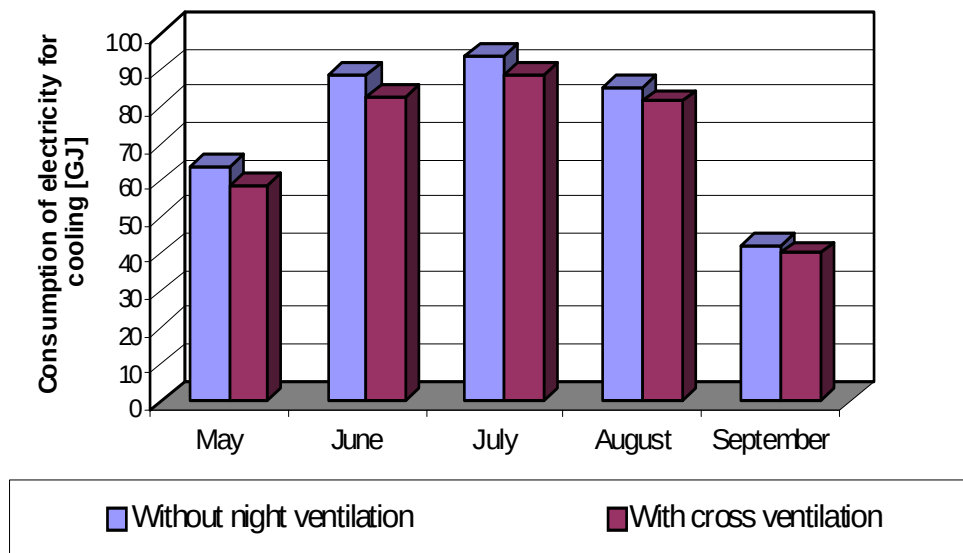


Fig. 7.24. Comparison of the seasonal consumption of electricity for the production of the cooling agent with and without night ventilation strategy

Calculations have shown that the application of night cooling ventilation in the analysed building is useful. It can reduce the production of the cooling agent by applying the fan-coil system and also reduces the installed cooling capacity. The highest percentage savings are achieved in May and June (Fig. 7.24). It has been found that generally modernisation reduces the annual cooling demand in offices by about six per cent.

Influence of different building parameters on possible energy savings

The results show how a building should be designed to achieve the most benefits of night cooling ventilation. In order to assess the effects of each parameter on the energy savings thanks to night cooling ventilation the case-study building was assumed as the reference case. The energy savings were calculated comparing the energy balance of the building with and without night cooling ventilation. Calculations were carried out for the month of May. The following night cooling ventilation systems have been analysed: stack ventilation, cross ventilation, single-side single opening ventilation, and mechanical balanced ventilation. Fig. 7.25-7.29 show the results of this analysis.

The results show that the effectiveness of cooling in night ventilation mostly depends on the following factors:

- Ventilation rate

A high ventilation rate during the night allows the thermal masses of the building to cool down and leads to higher energy savings for cooling. Energy savings in the reference building as a function of the ventilation rate are presented in Fig. 7.25.

➤ Internal gains.

Internal heat gains result from the occupants, electric devices, the sun, lighting and so on. They influence the heat and cooling demand. Studies have shown that the lower the heat gain, the more effective is the night-ventilation strategy (Fig. 7.26.).

➤ Infiltration airflow

The infiltration value significantly influences the energy balance of the building. Air flow through the cracks in the building envelope is undesirable. The amount of infiltrated air depends on natural driving forces (wind, temperature and humidity). The more air-tight the building is, the more energy-efficient is night ventilation (Fig. 7.27).

➤ Orientation

North orientation requires a minimum of energy for cooling, and this is why the least savings are achieved when night ventilation is applied. Maximum savings (due to the application of night cooling ventilation) are achieved in the case of west orientation of the building.

➤ Glazing ratio

A reduction in solar heat gains in the glazed surfaces results in larger energy savings from night cooling (Fig. 7.28). The lower the glazing ratio (lower solar heat gains), the higher are energy savings due to the application of night ventilation.

➤ Weight of the building

More thermal masses ensure higher savings in the application of night cooling ventilation. Results of calculations for different weights of the building are presented in Fig. 7.29.

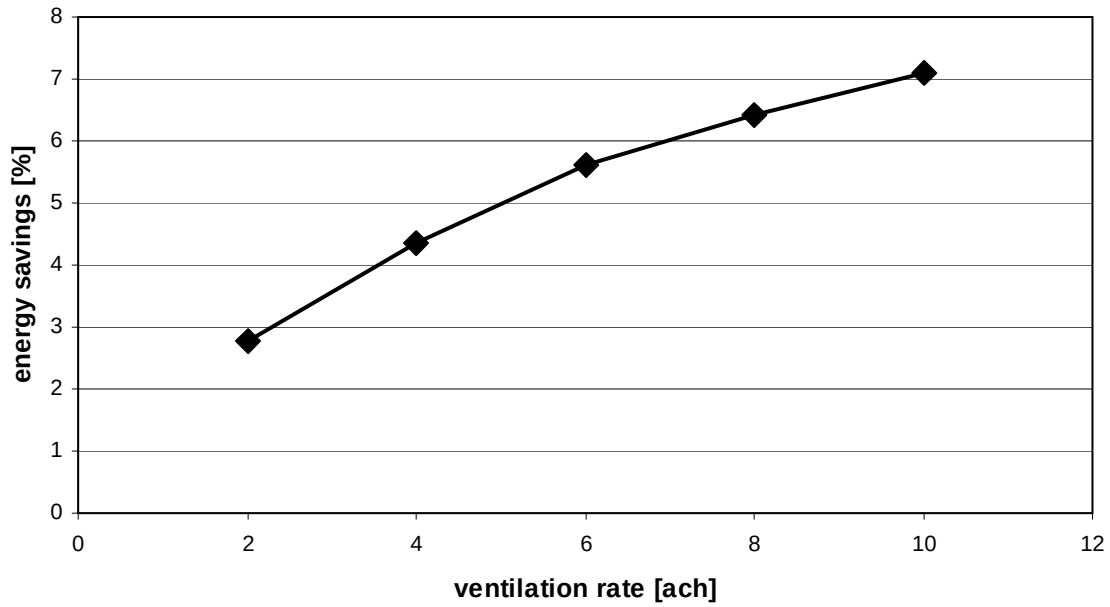


Fig. 7.25. Percentage of energy savings by using night cross ventilation as a function of the ventilation rate

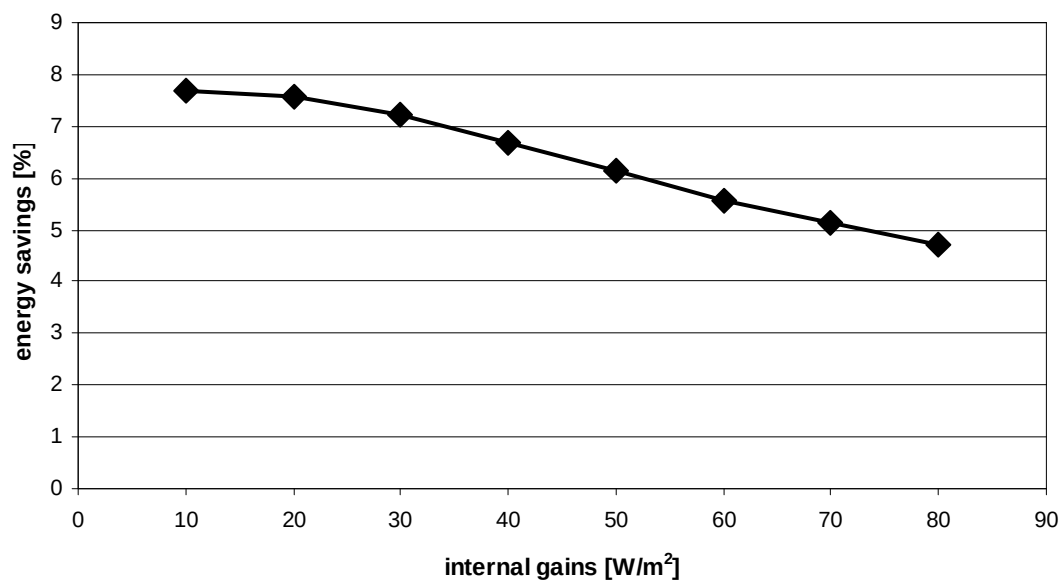


Fig. 7.26. Percentage of energy savings by using night cross ventilation as a function of internal heat gains

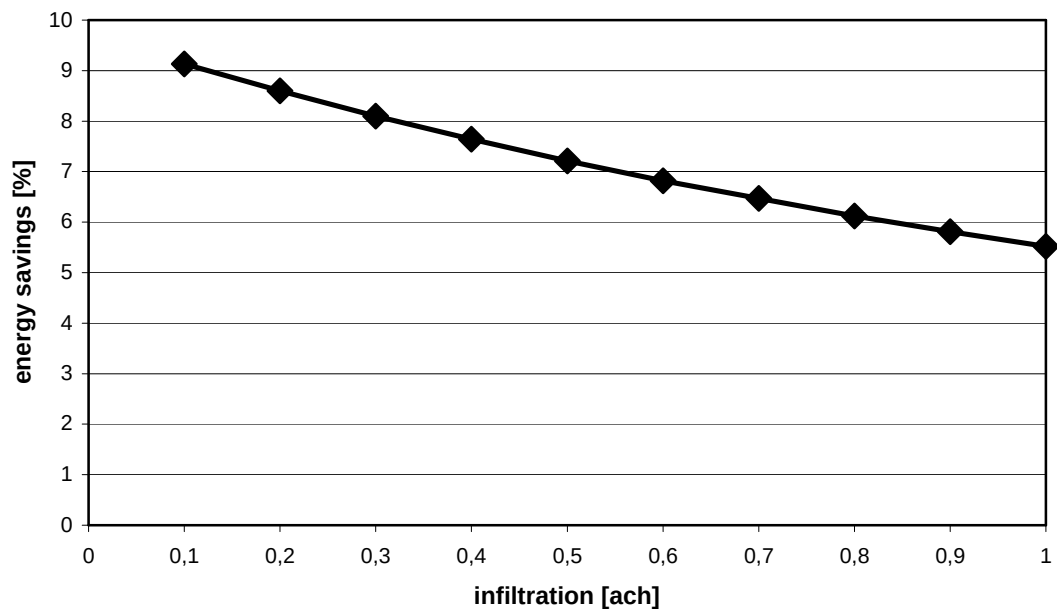


Fig. 7.27. Percentage of energy savings by using night cross ventilation as a function of the infiltration rate

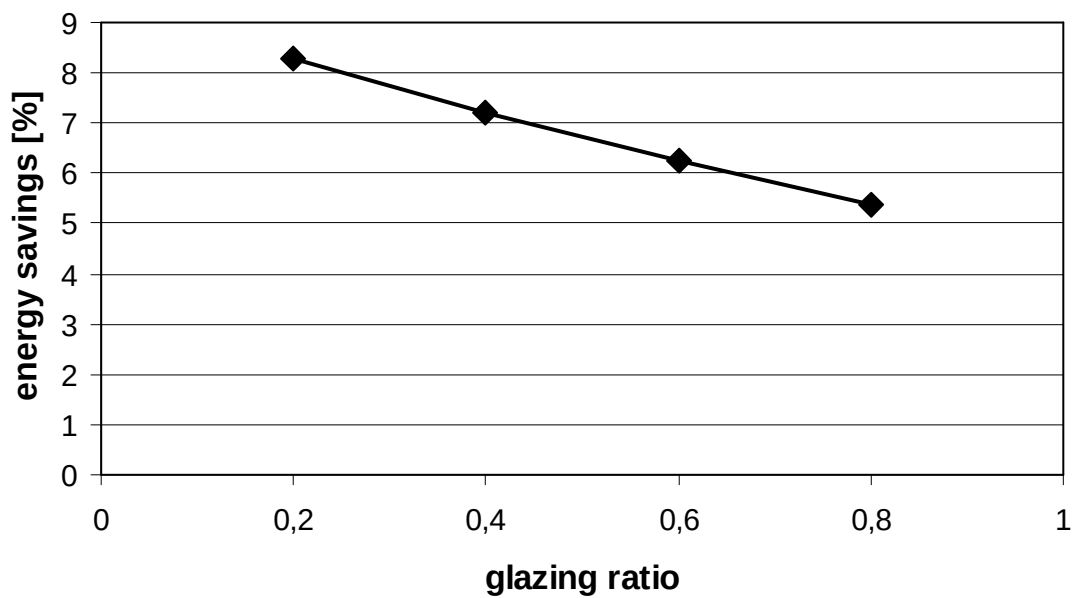


Fig. 7.28. Percentage of energy savings by using night cross ventilation as a function of the glazing ratio

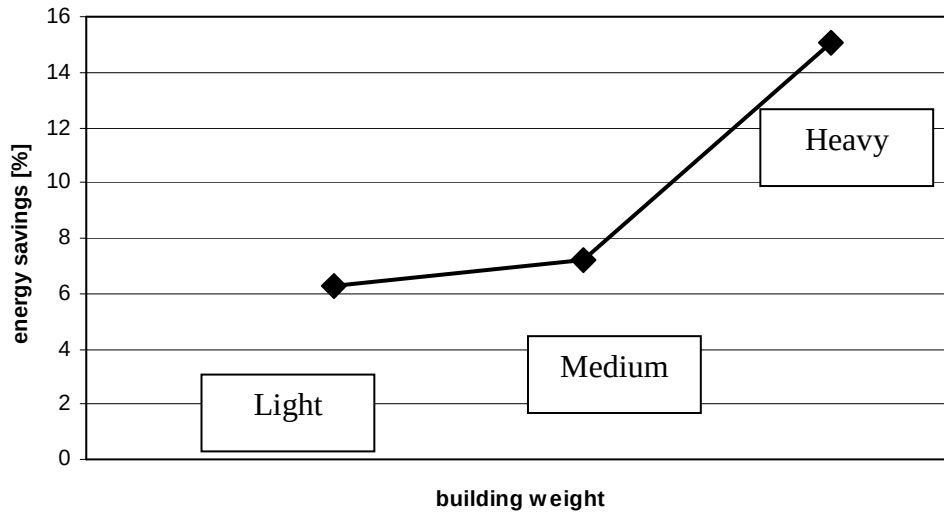


Fig. 7.29. Percentage of energy savings by using night cross ventilation as a function of the weight of the building

Analyses have shown that night cooling ventilation may ensure some energy savings if some of the building parameters are optimised (ventilation rate 10 ach “air changes per hour” or more, low internal heat gains, low infiltration rate, etc.). Fig. 7.30 illustrates the results of that optimisation: energy savings which can be achieved when the building has been designed for using night ventilation. All values of the designed parameters of the building are optimal ones from the point of view of energy savings.

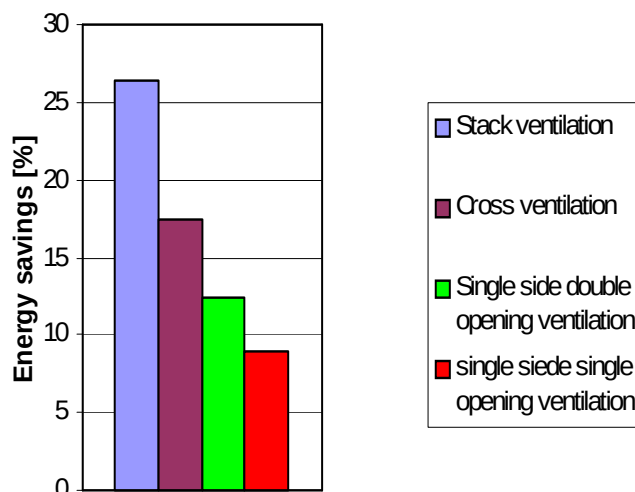


Fig. 7.30. Percentage of energy savings by using natural night ventilation at optimal building parameters

Example of systems analysis as a tool for investigating the influence of the application of night cooling ventilation on the energy balance of the case-study building

Process analysis of the application of night cooling ventilation in the building has shown that this strategy is beneficial and can decrease the cooling demand in the building, save cooling energy and decrease the installed peak cooling capacity. This modernisation influences the whole energy balance of the building. The influence on the energy balance can be investigated by systems analysis. In general, in the analysis of the energy effects due to the application of new techniques in the subsystem of consumers, the equation of the linear mathematical model of the energy balance of the analysed system is used. In the case of the application of night cooling ventilation in the analysed building we have:

$$\mathbf{G} + \mathbf{D} = \mathbf{A}\mathbf{G} + \mathbf{C}_1 + \mathbf{C}_2 + \mathbf{C}_3 + \mathbf{C}_4 \quad (7.11)$$

After transformations:

$$\mathbf{G} = (\mathbf{I} - \mathbf{A})^{-1} (\mathbf{C}_1 + \mathbf{C}_2 + \mathbf{C}_3 + \mathbf{C}_4 - \mathbf{D}) \quad (7.12)$$

where:

$\mathbf{G}$ - column matrix of the production of energy carriers,

$$\mathbf{G} = \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_{10} \end{bmatrix}$$

$\mathbf{D}$ - column matrix of the external supply of energy carriers,

$$\mathbf{D} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{10} \end{bmatrix}$$

$\mathbf{A}$ - matrix of flows between energy branches concerning the basic part of production,

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{110} \\ a_{21} & a_{22} & \cdots & a_{210} \\ \vdots & \vdots & & \vdots \\ a_{101} & a_{102} & \cdots & a_{1010} \end{bmatrix}$$

$\mathbf{C}$ - column matrix of the consumption of energy by the subsystem of consumers:

$$\mathbf{C} = \mathbf{C}_1 + \mathbf{C}_2 + \mathbf{C}_3 + \mathbf{C}_4 \quad (7.13)$$

$\mathbf{C}_1$ - column matrix of the consumption of energy concerning office rooms,

$\mathbf{C}_2$ - column matrix of the consumption of energy concerning auxiliary rooms,

$\mathbf{C}_3$ - column matrix of the consumption of energy concerning the standard equipment of the building.

$\mathbf{C}_4$ - column matrix of the consumption of energy in garages

$\mathbf{I}$ - unit matrix

The application of night cooling ventilation in the analysed building (modernisation which will save the energy consumption in the energy subsystem) will cause a reduction of the vector of the consumption of energy carriers $\mathbf{C}$ by the vector $\Delta\mathbf{C}$. These changes will also cause changes in the vector of production $\mathbf{G}$ by the vector $\Delta\mathbf{G}$. Thus, in the analysed case:

$$\Delta\mathbf{G} = (\mathbf{I} - \mathbf{A})^{-1} \Delta\mathbf{C} \quad (7.14)$$

where:

$(\mathbf{I} - \mathbf{A})^{-1}$ - inverse matrix

These changes are analysed for all energy carriers quoted in the input-output table:

- in the case of i -th energy carrier

$$\Delta G_i = A_{i1} \Delta C_1 + \dots + A_{ij} \Delta C_j + \dots + A_{i10} \Delta C_{10} \quad (7.15)$$

- concerning all energy carriers (in matrix notation)

$$\Delta \mathbf{G} = \underbrace{\begin{bmatrix} A_{11} & A_{12} & \dots & A_{110} \\ A_{21} & A_{22} & \dots & A_{210} \\ \vdots & \vdots & & \vdots \\ A_{101} & A_{102} & \dots & A_{1010} \end{bmatrix}}_{\text{elements of inverse matrix}} \times \begin{bmatrix} \Delta C_1 \\ \Delta C_2 \\ \vdots \\ \Delta C_{10} \end{bmatrix} \quad (7.16)$$

The application of night cooling ventilation in the case-study building can reduce the annual cooling demand in the offices $\overline{Z_{11}}$. The electricity consumption in offices will also be reduced because of the reduced running time of fan-coil units. That change also causes changes in the consumption and production of other energy carriers in the building. Table 7.15 is the main input-output table concerning this case-study building. The shaded items include values and coefficients which have been changed after the modernisation. The modernisation will cause a reduction in the vector of consumption of energy carriers C by the vector ΔC :

$$\Delta C = \begin{bmatrix} -63.51 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -9 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

All calculations in this part of the investigations have been made using the program Engineering Equation Solver. Table 7.14 shows input data which have been changed after the application of night cooling ventilation. All vectors of the consumption of energy carriers with new values (the grey cells) of the subsystem of consumers (office rooms, auxiliary rooms, garages and standard equipment of the building) are shown in Table 7.16. Using the results of the mathematical model, the inverse matrix of energy flows between the energy

branches has been calculated (Table 7.17). On the basis of the formulated inverse matrix and the vector ΔC , the vector ΔG has been calculated:

$$\Delta G = \begin{bmatrix} -63.51 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -38.06 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Electricity is not produced in the building (there is no CHP or BCHP unit), so that the calculated electricity savings concern its supply. Table 7.18 shows the new vector of values of the production and supply after the modernisation. The shaded items include values which have been changed after the application of night ventilation. Table 7.19 shows a comparison of the results of the systems analysis before and after the considered modernisation. Studies have shown that after the application of night ventilation the annual cooling production decreases from 1128 GJ to 1065 GJ and saves 38 GJ electric energy annually.

Tab. 7.14. Input data to the system analysis of application of night cooling ventilation to the building

Description	Unit	Symbol	Before modernisation	After modernisation
Annual cooling consumption in offices	GJ/a	$\overline{Z_{11}}$	1058,58	995,07
Annual electricity consumption in offices (reduction of the running time of fan-coil units and, because of that, reduction of electricity consumption by the fan-coil system).	GJ/a	$\overline{Z_{71}}$	2639,22	2630,22

Tab. 7.15. Input-output table for case-study building. Red cells mark values which changed after the considered application of night ventilation

[illegible]

Tab. 7.16. Vectors of values of consumption of energy carriers $\bar{Z}_{i_k}$ in technological subsystem after modernisation

Technological consumers				
	Office rooms	Auxiliary rooms	Garages	Standard equipment of building
1	995,07	0	0	0
2	0	851,8	0	0
3	0	994,6	0	0
4	1677,11	0	0	0
5	45544,8	30363,2	0	0
6	0	0	435591	0
7	2630,22	79,22	397,33	246,7
8	0	10085	0	0
9	0	576	0	0
10	0	0	0	0

Tab. 7.17. Inverted matrix $(E-A)^{-1}$ of energy flows between energy branches.

	Energy carrier	1	2	3	4	5	6	7	8	9	10
1	Cooling medium (water–glycol) 6/12° C	1	0	0	0	$9.19 \cdot 10^{-4}$	0	0	0	0	0
2	Hot process water 85/55 ° C	0	1	0	0	$1.286 \cdot 10^{-2}$	0	0	0	0	0
3	Hot tap water	0	0	1	0	0	0	0	0	0	0
4	Hot process water (fan coil) 60/45 ° C	0	0	0	1	0	0	0	0	0	0
5	Air from air- conditioning unit	0	0	0	0	1	0	0	0	0	0
6	Air from garages	0	0	0	0	0	1	0	0	0	0
7	Electricity	0.4576	$2.413 \cdot 10^{-2}$	$3.64 \cdot 10^{-3}$	$4.699 \cdot 10^{-3}$	$4.287 \cdot 10^{-3}$	$8.905 \cdot 10^{-4}$	1	0	0	0
8	Drinking water	0	0	1	0	0	0	0	1	0	0
9	Network natural gas	0	0	0	0	0	0	0	0	1	0
10	Heat from heat plant	0	1	0,1715	1	$1.286 \cdot 10^{-2}$	0	0	0	0	1

Tab. 7.18. Vectors of values of production G_i and supply D_i of energy carriers

	Energy carrier	Unit	Production G	Supply D
1	Cooling medium (water-glycol) 6/12° C	GJ	1065	0
2	Hot process water 85/55 °C	GJ	1828	0
3	Hot tap water	t	994,6	0
4	Hot process water (fan coil) 60/45 °C	GJ	1677	0
5	Air from air- conditioning unit	t	75908	0
6	Air from garages	t	435591	0
7	Electricity	GJ	0	4570
8	Drinking water	t	0	11080
9	Network natural gas	GJ	0	576
10	Heat from heat plant	GJ	0	3675

Tab. 7.19. Results of systems analysis:

Description	Unit	Symbol	Before modernisation	After modernisation
Annual cooling production	GJ/a	G_1	1128	1065
Annual consumption of electricity for cooling production	GJ/a	Z_1	548,2	519,2
Annual consumption of electricity by the building	GJ/a	D_7	4608	4570

The analysis has shown that night ventilation is a low-energy cooling method that may reduce the energy demand for the mechanical cooling system and provides comfortable internal conditions. An optimal solution for the case-study building would be a system with cross ventilation. Calculations have shown that the application of night cooling ventilation in the analysed building is useful. Most energy savings are achieved when night cooling ventilation operates from 8 p.m. to 7 a.m. That method of night ventilation reduces the cooling demand for the fan-coil system and also reduces the installed cooling capacity. Most savings are achieved in May and June. The application of night ventilation reduces the annual cooling demand in offices by about six per cent. Systems analysis of the effects of this application shows that the annual supply of electricity can be reduced by about 38 GJ. That value is not large in comparison with electricity consumption by the whole building.

7.7. Example of systems approach to the analysis of the application of a CHP unit for complex buildings

The systems analysis may be useful for assessing the energy effects of changes in the energy subsystem of a building. An example of such a change is the application of a CHP unit in the case-study building. The application of the CHP unit decreases the demand for electricity and heat supplied from outside. In this complex building electricity produced by the CHP unit is a by-product and heat is the main product (according to the cogeneration model of a system CHP plant). Heat produced by the CHP unit is completely consumed inside the building. In periods with a high heat demand additional heat is produced by a peak gas boiler. The coefficient of the by-production of electricity results from the CHP factor:

$$f_{87} = (1 - \epsilon)\sigma \quad (7.17)$$

where ϵ denotes the share of peak heat in the overall heat production.

By-production of the electricity U_{87} is calculated from the relation:

$$U_{87} = f_{87} G_7 = (1 - \epsilon) \sigma G_7 \quad (7.18)$$

where G_7 denotes the overall heat production in the analysed building.

The consumption of the chemical energy of natural gas is calculated using the method of avoided fuel expenditure. This method was formulated in compliance with the method of avoided costs and states that electricity production in the CHP unit should be charged with

the same consumption of chemical energy of fuels as in the equivalent (replaced) system power plant which produces the same amount of electricity. Hence:

$$Z_{9\ 8} = \frac{U_{8\ 7}}{\eta_{El\ g}} \quad (7.19)$$

where:

- $Z_{9\ 8}$ – chemical energy consumption of natural gas for electricity production in the considered CHP unit,
- $\eta_{El\ g}$ – energy efficiency of the equivalent (replaced) gas power plant.

In that case the consumption of the chemical energy of natural gas for heat production is calculated from the relation:

$$Z_{9\ 7} = \frac{(1-\varepsilon)G_7 + U_{8\ 7}}{\eta_{E\ CHP}} + \frac{\varepsilon G_7}{\eta_{E\ pb}} - \frac{U_{8\ 7}}{\eta_{El\ g}} \quad (7.20)$$

Hence the coefficient of unit consumption of the chemical energy of natural gas for heat production:

$$a_{9\ 7} = \frac{Z_{9\ 7}}{G_7} = \frac{(1-\varepsilon)(1+\sigma)}{\eta_{E\ CHP}} + \frac{\varepsilon}{\eta_{E\ k\ sz}} - \frac{(1-\varepsilon)\sigma}{\eta_{El\ g}} \quad (7.21)$$

where:

- $\eta_{E\ CHP}$ – energy efficiency of the CHP unit in the considered complex building,
- $\eta_{E\ pb}$ – energy efficiency of the considered gas peak boiler in the complex building.

Savings of the chemical energy of natural gas achieved thanks to the CHP production:

$$-\Delta E_{ch} = \frac{(1-\varepsilon)G_7}{\eta_{E\ hg}} + \frac{U_{8\ 7}}{\eta_{El\ g}} - \frac{(1-\varepsilon)G_7 + U_{8\ 7}}{\eta_{E\ CHP}} \quad (7.22)$$

where $\eta_{E\ hg}$ denotes the energy efficiency of the gas heating plant. With reference to a unit of heat production we get:

$$\frac{-\Delta E_{ch}}{G_7} = (1-\varepsilon) \left(\frac{1}{\eta_{E\ hg}} + \frac{\sigma}{\eta_{El\ g}} - \frac{1+\sigma}{\eta_{E\ CHP}} \right) \quad (7.23)$$

Coefficient of Primary Energy Savings (PES):

$$PES = \frac{-\Delta E_{ch}}{E_{chr}} \quad (7.24)$$

where E_{chr} denotes the chemical energy in the separate production of heat and electricity.

$$PES = 1 - \frac{\frac{1+\sigma}{\eta_{E_{CHP}}}}{\frac{1}{\eta_{E_{hg}}} + \frac{\sigma}{\eta_{E_{elg}}}} \quad (7.25)$$

In the case of the complex building under analysis the coefficient of the Primary Energy Savings equals $PES=0,31$. Cumulative chemical energy savings are expressed by the relation:

$$-\Delta E_{ch}^* = \frac{-\Delta E_{ch}}{\eta_{pdg}^*} \quad (7.26)$$

where: η_{pdg}^* denotes the cumulative energy efficiency of gaining the and supply of natural gas.

In this case of modernisation of the energy subsystem a CHP unit with a piston gas engine has been proposed. Input data for this analysis have been gathered in Table 7.20.

Tab. 7.20. Input data for the analysis of application of the CHP unit

Heat demand by the analysed building	$Q=3675,66 \text{ GJ/year}$
CHP factor in the cogeneration unit	$\sigma=0,65$
Energy efficiency of CHP unit	$\eta_{E_{CHP}} = 0,77$
Energy efficiency of peak gas boiler	$\eta_{E_{k sz}} = 0,85$
Share of peak heat in overall heat production	$\epsilon=0,1$
Energy efficiency of gas heating plant	$\eta_{E_{cg}} = 0,85$
Energy efficiency of equivalent (substituted) gas power plant	$\eta_{E_{elg}} = 0,339$

Results of calculations – energy consumption and coefficients of energy consumption in energy branches are presented in Tables 7.21 and 7.22.

The application of the CHP unit in a complex building changes the structure of its energy subsystem. The consumption of energy carriers in the subsystem of consumers is the same as before its modernisation.

The presented example of the calculation concerning the rationalisation of the energy management of complex buildings thanks to the application of the CHP system indicates that in this case the structure of the energy subsystem is changed. The consumption of energy carriers by the consumers does not undergo any changes (which was the case when night ventilation was applied – section 7.6). Calculations have shown that the demands for electricity in the complex buildings covered by the CHP unit as a by-product was reduced. The production of electricity in the cogeneration system involves savings in the chemical energy of fuels in cogeneration in comparison with separate production of heat and electricity. In the considered case the cumulative savings in the chemical energy of fuels amount to $-\Delta E_{ch}^* = 3210 \text{ GJ}$. The value of the index PES=0.31 proves the high energy efficiency of the modernisation of the energy management in complex buildings.

Tab. 7.21. Results of the analysis

	Energy carrier	Unit	Production	Supply	INTERBRANCH FLOWS										SUBSYSTEM OF CONSUMERS			
					1	2	3	4	5	6	7	8	9	10	Offices	Auxiliary rooms	Garages	Standard equipment of building
1	Cooling medium 6/12°C	GJ	1128.339452		0	0	0	0	0.000919	0	0	0	0	0	1058.58	0	0	0
2	Hot process water 85/55 °C	GJ	1827.97688		0	0	0	0	0.01286	0	0	0	0	0	0	851.8	0	0
3	Hot tap water	Mg	994.6		0	0	0	0	0	0	0	0	0	0	0	994.6	0	0
4	Hot process water 60/45 °C	GJ	1677.11		0	0	0	0	0	0	0	0	0	0	1677.11	0	0	0
5	Air from air-conditioning unit	Mg	75908		0	0	0	0	0	0	0	0	0	0	45544.8	30363.2	0	0
6	Ventilation air for garages	Mg	435591		0	0	0	0	0	0	0	0	0	0	0	0	435591	0
7	Heat	GJ	3675.66078		0	1	0.1715	1	0	0	0	0	0	0	0	0	0	0
8	Electricity	GJ	2150	2516.84231	0.4858	0.02413	0.00364	0.004699	0.003556	0.00089	0	0.020005	0	0	2639.22	79.22	397.33	246.7
9	Natural gas	GJ		8097	0	0	0	0	0	0	2.046163	0	0	0	0	576	0	0
10	Drinking water	Mg		11079.6	0	0	1	0	0	0	0	0	0	0	0	10085	0	0

Tab. 7.22. Results of the analysis

	Energy carrier	Unit	Production	Supply	INTERBRANCH FLOWS										SUBSYSTEM OF CONSUMERS			
					1	2	3	4	5	6	7	8	9	10	Offices	Auxiliary rooms	Garages	Standard equipment of building
1	Cooling medium 6/12°C	GJ	1128.339452		0	0	0	0	69.75945	0	0	0	0	0	1058.58	0	0	0
2	Hot process water 85/55 °C	GJ	1827.97688		0	0	0	0	976.1769	0	0	0	0	0	0	851.8	0	0
3	Hot tap water	Mg	994.6		0	0	0	0	0	0	0	0	0	0	0	994.6	0	0
4	Hot process water 60/45 °C	GJ	1677.11		0	0	0	0	0	0	0	0	0	0	1677.11	0	0	0
5	Air from air-conditioning unit	Mg	75908		0	0	0	0	0	0	0	0	0	0	45544.8	30363.2	0	0
6	Ventilation air for garages	Mg	435591		0	0	0	0	0	0	0	0	0	0	0	0	435591	0
7	Heat	GJ	3675.66078		0	1827.977	170.5739	1677.11	0	0	0	0	0	0	0	0	0	0
8	Electricity	GJ	2150	2516.84231	548.1473	44.10908	3.620344	7.88074	269.9288	387.676	0	43.01	0	0	2639.22	79.22	397.33	246.7
9	Natural gas	GJ		8097	0	0	0	0	0	0	7521	0	0	0	0	576	0	0
10	Drinking water	Mg		11079.6	0	0	994.6	0	0	0	0	0	0	0	0	10085	0	0

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Chapter 8

LIFE CYCLE ASSESSMENT OF ENERGY SYSTEMS IN COMPLEX BUILDINGS

Life cycle assessment (LCA) is a full cycle-of-life analysis concerning the evaluation of hazards menacing the environment, connected with products or services burdened by the consumption of energy and materials which leads to the depletion of natural resources and affects both the quality of ecosystems and human health. As far as complex buildings are concerned, their full life cycle comprises the extraction of mineral raw materials and primary energy, as well as the production of building materials, the construction of buildings, their exploitation, and demolition connected with the recycling of building materials. LCA contains the following stages: definition of the goal and scope, inventory analysis, impact assessment, and interpretation. The second stage, also called life cycle inventory (LCI) analysis, consists in completing a database concerning the supply of energy and raw and other materials, information about main and by-production, amounts of noxious emissions, and other environmental effects. In the case of complex systems (e.g. complex buildings), as an algorithm of setting up material-energy balances, input-output analysis ought to be applied. In the third stage, the respective environmental burdens are expressed as corresponding categories affecting the environment (e.g. acidification, eutrophication, greenhouse effect and ozone depletion) in compliance with accepted international references.

As an example, an LCA was carried out concerning an office building making use of the ENVEST program. The number of “Ecopoints” generated by the respective structural elements of the building and all the services applied in the building have been assessed.

8.1. Principles of the energy-ecological analysis in the full cycle of life (LCA)

LCA is a method for evaluating the whole environmental impact of a product or process. LCA begins with the extraction of raw materials, then deals with the production and consumption of the product or process up to decommissioning (disposal or recycling). Such an analysis may concern both goods and services. An exact definition of LCA is:

“LCA – a technique aiming at the assessment of hazards for the environment connected with products or services, both by identification and quantitative evaluation of the consumed materials and energy, as well as wastes emitted to the environment and also the

assessment of the effect of materials, energy and wastes on the environment. This assessment concerns the full cycle of life of the product or service, starting with extracting and processing of mineral raw materials, the production process of goods, distribution, consumption, secondary utilisation and final decommissioning and transport” [1].

Thus, LCA serves to determine the influence of the analysed factors on the environment and permits the stage of the process in which a hazard is at its greatest to be indicated. Effects on the environment are assessed by quantitative analysis of the consumption of materials and energy from the point of view of cumulative energy consumption of primary fuels as well as identification of the generated pollutants, together with an assessment of their influence on the environment. LCA is not directly concerned with an economic analysis of the evaluated product or social aspects of the assessed operations.

In its early days LCA was primarily used for comparison of products; for example, to compare the environmental impacts of disposable and reusable products. Today its applications include government policy, strategic planning, marketing, consumer education, process improvement and product design.

Three groups of hazards affecting the environment can be distinguished, viz.[1, 13]:

- effect on the quality of ecosystems (e.g. contamination of the atmosphere, soil and water, and disposal of wastes),
- effect on human health (e.g. occupational diseases and safety of work),
- depletion of natural resources involving, for example, the degradation of sites and changes in the structure of the underground water system.

LCA may be applied to both for the determination of the influence of the life cycle of a product or service on the environment (e.g. in a comparative analysis of various solutions) and the determination of the most important reasons for the effect of the given product or service on the environment.

Generally, the full life cycle of a product comprises:

- extraction of raw materials, including fuels, leading to the depletion of natural resources,
- the manufacture of products,
- utilisation of the products (exploitation),
- decommissioning connected with the utilisation of wastes.

Such a division is characteristic for typical goods (e.g. cars). In the case of energy carriers (e.g. electricity) LCA comprises the following components [4, 5, 6, 7]:

- extraction of fuels (e.g. power coal) and non-energy raw materials (e.g. limestone),
- construction of power stations,
- exploitation of power stations – production of electricity,
- decommissioning of power stations – utilisation of wastes (e.g. scrap) and recultivation of the sites.

A typical life cycle of a product or service is shown in Figure 8.1.

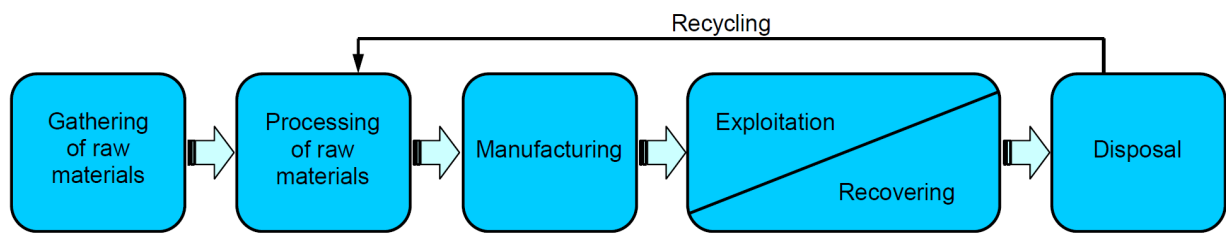


Fig. 8.1 Typical life cycle of a product or service

The inclusion of life cycle costs (LCC) in LCA permits the ecological and economic aspects to be combined, facilitating the taking up of decisions. It is essential to take into account the influence of transport of respective materials on the environment.

LCA is connected with the following procedures [1]:

- definition of the system of the product, which is to be understood as a purposely determined set of unit processes and the material-energy relations between them,
- determination of the boundary of the system of the product; usually, the balance shield constitutes its boundary, and what surrounds the system of the product comprises the natural environment and the systems of other products; the interconnections between any given system with other systems may be strong or weak; the boundary of the system is also to be understood in the sense of time and geographical area,
- definition of the functional unit; that is, a quantifiable effect of the system serving as a unit of reference in the LCA.

In most cases LCA is carried out in four stages (Fig. 8.2)

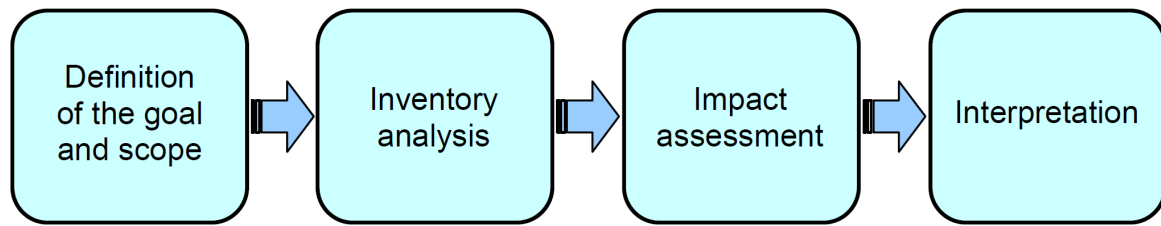


Fig. 8.2. Stages (steps) of LCA

The aim in the first stage of LCA is to determine the exact details of the boundaries and level of the analysis. The boundaries of the system define the set of unit processes included in the analysis. The set of unit processes together with relations existing between them form the so-called system of the product. The unit process ought to be understood as the smallest part of the system of the product for which the input data are gathered.

During the second stage, the following data are gathered for each unit process:

- data concerning the amount of supplied energy and raw and other materials,
- information concerning main and by-products, as well as the amount of wastes,
- the amount of noxious emissions contaminating the air, water and soil, as well as other environmental effects (e.g. occupation of the sites).

The input and output quantities should refer to the functional unit. In the case of cogeneration or coupled processes comprising more than one useful product, the input and output quantities ought to be divided either in compliance with the principle of avoided expenditures (as in the case of avoided costs) or according to the code of division acceptable in the concrete multi-productive process. For example, the exergy code may be applied in an air separation unit (ASU) producing technical gases or CHP producing several fluxes of process steam with different pressure levels.

In the third stage of LCA the effect of the input and output fluxes is assessed. The respective environmental charges are expressed as corresponding categories of effects on the environment, mostly in compliance with the accepted international references. Next, the index of the given category of effect on the environment is calculated. For this purpose, models specialised for each concrete category of effects are applied.

Stage four comprises the following steps:

- identification of the main factors influencing the given category of effects (determination of the share of the respective phases of LCA in the given category),

- assessment of the credibility of the achieved results; the completeness of information is checked, and the sensitivity and uncertainty are analysed,
- evaluation of the LCA report by independent experts,.

Applications of LCA include:

- assessment of the effect of the product or service on the environment,
- identification of localities in which the negative influences on the environment can be reduced in each stage of the life cycle of the product,
- designing processes friendly to the environment,
- comparison of products with respect to their environmental hazards,
- promotion of pro-ecological technologies.

Exergetic life cycle assessment (ELCA) may also be applied [5]. The criterion for evaluating any process is in this case the life cycle irreversibility of the product. Such an analysis permits to detect the locality of excessive losses of exergy during the whole life cycle. With this method the degree of utilisation of fossil fuels and raw materials and the efficiency of their utilisation can be evaluated. The ecological components are taken into account by adding the additional exergy losses during the process of reducing emissions to the lowest technically achievable value.

8.2. Life cycle inventory analysis

The second stage of LCA is connected with the so-called LCI (life cycle inventory) phase, which is an analysis concerning the set of inputs and outputs of the system of the product [21]. This analysis is based on material-energy balances, which are used to quantify the consumption of energy, the depletion of non-renewable resources of primary energy, and emissions in processes taking place between the stages of raw materials including fossil fuels and the final product. The algorithm of the LCI analysis depends on the complexity of the system of interconnections. Figure 8.3. presents a serial system of connections between the fossil fuel stage (natural gas) and the final product (heat). This approach to the LCI phase is also called analysis of the chain of processes. This is a simplified approach assuming a lack of strong connections with other branches of the economy in the given country.

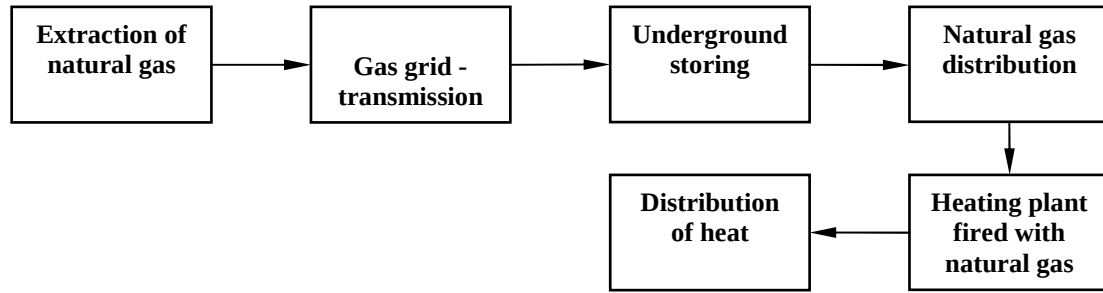


Fig.8.3. Simplified diagram of interconnections in the LCI analysis

Figure 8.4. presents a system of interconnections which is closer to reality, taking into consideration the connections between the domestic-energy system and the system of steel production. In this case the system of interconnections is not a serial one but is characterised by feedback connections.

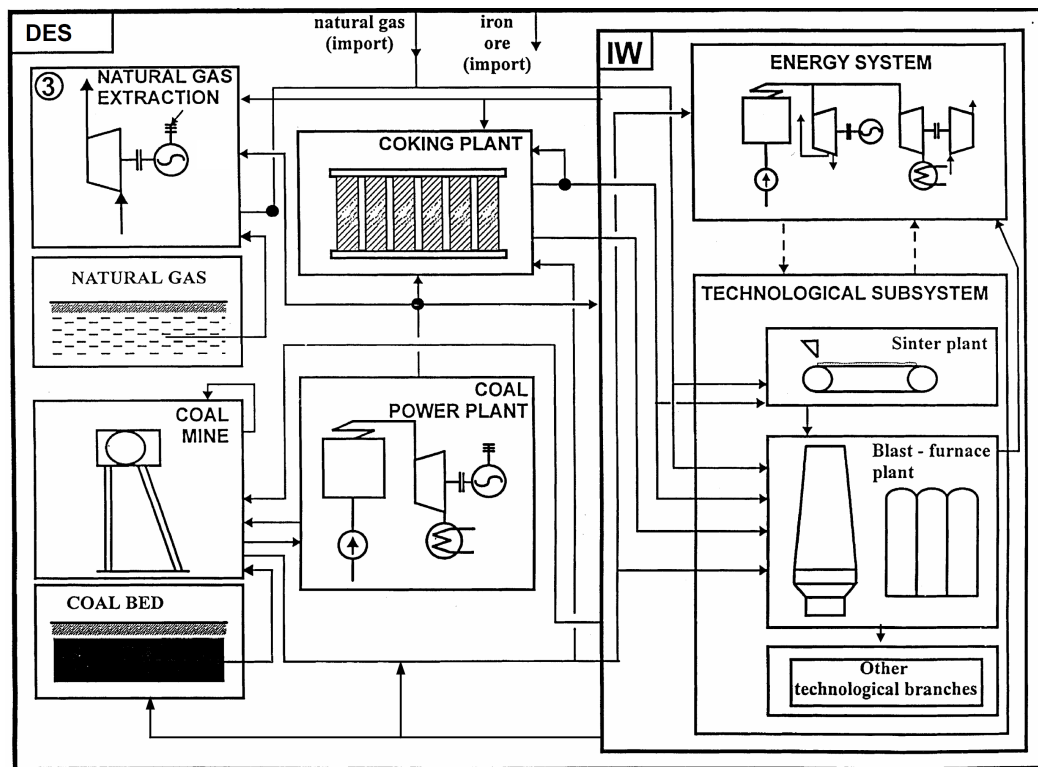


Fig. 8.4. Exemplary complex system of interconnections between ironworks and the domestic energy system; DES - domestic energy system; IW - ironworks

The diagram presented in Figure 8.4. concerns the production of finished steel, taking into account close connections with the electro-energy system of the production of coke as well as the extraction of hard coal and natural gas. For the complex system of

interconnections as an algorithm of setting up material-energy balances, input-output analysis is recommended. Very often the connection of the sequential method of process analysis with input-output analysis is the best approach.

Besides the uncertainty of input data (usually the main reason) the mathematical models lead to uncertain results in LCA due to the incomplete reliability of the model and incompleteness resulting from the incoherence of its respective elements [1]. Every mathematical model renders reality only approximately. LCA is always a compromise between scientific accuracy and practical application. Therefore, it is to be recommended to keep in mind that there is a group of processes strongly affecting the results of LCA. In order to separate the important parameters from the unimportant ones, a sensitivity analysis should be applied.

The factors leading to the uncertainty of input data are external and internal ones [1]. The former belong to connections with what surrounds the system of the product; that is, with other systems (other branches of the economy) and the natural environment, comprising, for example, the duration curve of ambient temperature, which affects the heat demand for heating. The availability of fuels, which may necessitate a substitute feedstock in the energy system, is also an external factor. To the internal factors belong, first of all, the energy characteristics of machines and energy devices such as, for example, energy efficiency and availability. The uncertainty of input data deteriorates with time. This is a specific problem in LCA, similar to the problem of optimisation in the case of the uncertainty of input data (Chapter 3).

8.3. Ecological components of LCA

LCA arose as a calculation technique in response to the increasing social awareness of the importance of protecting the environment and the possibility of ecological control of the production and consumption of goods. The ecological profile of a product can be determined by means of LCA, from the extraction of raw materials and fuels up to the final utilisation of the system of the product. The starting point in the electro-energy system, for example, is the fuel cycle for gaining the main fuel (e.g. power coal or natural gas). The next stages comprise the construction, exploitation and decommissioning of the power unit, if the LCA concerns the balance sheet of the power unit, and also the construction, exploitation and decommissioning of the networks, if the LCA has taken into account the consumers.

As in energy analysis, the indices of cumulated emissions may be calculated based on the assumption that the average indices of cumulative emissions concerning energy carriers (mainly fuels) of the given country and materials provided from outside are known. Such an approach, already mentioned in the case of energy analysis, is based on the assumption that the effect of the production of the analysed system of the product on the mean values of the indices of cumulative emissions in the given country may be neglected. This means that the analysed system of interconnections is a set of weak interconnections.

Generally the harmful effects of an energy system on the environment may be collated in two groups:

- disturbance of the ecological equilibrium due to the emission of harmful substances,
- depletion of non-renewable natural resources.

Processes of extraction of primary fossil fuels are connected with the following risks:

- the risk to the life and health of miners,
- mining damages,
- salinity of mine water,
- depression craters in strip mines,
- losses of hard coal resources,
- leaking of liquid fuels,
- explosion hazards of gaseous fuels,
- hazards due to the radiation of nuclear fuels and wastes.

Mining wastes are dusty in the course of their transport and storage in a dry state, and cause the contamination of groundwater and surface water in their wet state [16]. A depression crater lowers the level of groundwater, which negatively affects vegetation and leads to the drying up of wells. Mine water contains dissolved mineral salts, particularly NaCl. Na^+ and Cl^- ions, which disturb the physicochemical and biological equilibrium. Due to salinity, biological life is hampered. Mine water also contains dissolved salts of radioactive radium ^{226}Ra . Hazards are caused by radioactive sediments containing insoluble radium salts. Resources of hard coal which remain in a strongly contaminated stage due to gophering are irreclaimable losses.

The conversion of fossil fuels to electricity and heat results in the formation of contaminations such as dust, sulphur and nitrogen oxides, CO, soot, hydrocarbons, aldehydes, mercury, and CO_2 .

Waste heat from a condensing power station is removed by means of open or closed water circulation. Carrying away the heat with cooling water to water reservoirs or rivers may negatively affect biological life. The rise of temperature in the water reduces the content of oxygen in the water and hampers the growth of microorganisms (purification of the water from harmful microbes). Considerable irreclaimable losses in cooling towers increase deficiency of water. Cooling towers deteriorate the microclimate in the vicinity of power stations, particularly in winter. The construction of water reservoirs at hydropower stations also negatively affects the environment. The level of groundwater rises, and the terrain in the vicinity of a water reservoir is flooded. Also the banks are undermined due to continuous changes in the water level of the reservoir. The operation of a nuclear power station leads to thermal water pollution and may cause radioactive contamination of the water and air. The transmission of the electricity by means of overhead grids leads to the formation of an electromagnetic field, which negatively affects both people and animals.

The emission of dust containing particles of soot, metallic and non-metallic elements causes:

- diseases of the respiratory tracts,
- changes in the nervous system and the blood,
- carcinogenic effects,
- hampering of photosynthesis,
- corrosion of metals.

Dusts are formed by organic and mineral substances of fuels and particles of soot resulting from the conversion of fuels. Metallic particles result from the condensation of metal vapours. Dust also contains radioactive substances. Particularly severe are emissions of minute particles of dust (less than $20\ \mu m$), not retained by electrofilters. In unfavourable atmospheric conditions they remain in the air for quite a long time, and the human organism does not possess any effective natural protection against them. On the dust particles suspended in the air particles of sulphur and nitrogen oxides may deposit, forming “smog”.

Metallic and non-metallic elements contained in the dust in the form of compounds lead to the following harmful effects:

- arsenic compounds, which are strong poisons,
- lead, which causes permanent changes in the nervous system and the blood,
- iron and silicon, which cause dust disease,

- calcium, which may lead to acute pneumonia and irritates skin and mucous membranes.

Sulphur and nitrogen oxides cause:

- diseases of the respiratory tracts,
- carcinogenic effects,
- “acid rains”- deforestation,
- corrosion of metals and damage to buildings.

Carbon oxide decreases the ability of blood to transport oxygen, affects the nervous system, and leads to diseases of the respiratory tracts. Aromatic hydrocarbons exert carcinogenic effects. Carbon dioxide, emitted in excessive amounts, disturbs ecological equilibrium on the Earth.

Organic pollutants, such as hydrocarbons, tarry substances and benzo-a-pyrene, result from the incomplete combustion of hydrocarbon fuels or the pyrolysis of fuels. An increase in temperature of the combustion effects a reduction in the emission of organic pollutants. This, however, leads to an increased emission of nitrogen oxides.

The kinds of emitted hydrocarbons depend on the kind of fuel used and the way it is combusted, as well as on the operation of installations purifying the flue gases. Among pollutants of this kind aliphatic and aromatic hydrocarbons dominate, some of them being polycyclic aromatic hydrocarbons (PAH) formed in the course of combustion. PAH hydrocarbons released into the atmosphere are either volatile or adsorbed on the surface of dust (such as soot and volatile ashes). From among 26 PAH hydrocarbons in the atmosphere some are carcinogenic and mutagenic. Benzo-a-pyrene is one of the most harmful ones.

Acidification

Nitrogen and sulphur oxides are hydrated in the atmosphere, dropping down on Earth in the form of acids contained in rain, snow and fog or as dry particles. These are co-called “acid rains” resulting in deforestation. Acid rains lead to the leaching of nutrient elements in the soil such as calcium, magnesium and potassium. Moreover, aluminium affected by acid rains infiltrates the roots of plants in large amounts, precipitating phosphorous compounds in their cells. This leads to a blockage of the roots systems and withering of the plants. Acid rains and heavy metals act synergistically hampering the growth of trees (particularly coniferous ones). Acid rains damage the life in water areas. Fish perish at $\text{pH} < 4,5$.

An example of an ecological time bomb is what happened in Big Elk Lake in the United States where in the course of 50 years (1930-1980) biological life decayed due to the emission of large amounts of sulphur by nearby industrial plants and the resulting acid rains. The buffering of both the soil drainage area and the lake itself was exhausted. Since 1980 this lake has been dead [22].

Emissions affecting the acidification of soil comprise SO_2 , NO_x , NH_3 , HCL and HF . Emissions of acidifying agents are recounted into an equivalent of SO_2 assuming the following coefficients:

$$1 \text{ kg NO}_x = 0.7 \text{ kg eq. SO}_2$$

$$1 \text{ kg NH}_3 = 1.88 \text{ kg eq. SO}_2$$

$$1 \text{ kg HCL} = 0.88 \text{ kg eq. SO}_2$$

$$1 \text{ kg HF} = 1.6 \text{ kg eq. SO}_2$$

Eutrophication of the environment

Sewage disposal of phosphorus, carbon and nitrogen compounds into rivers and water reservoirs leads to eutrophication. Eutrophication is the process of enrichment with nutrients. Evident results of eutrophication are an abundant growth of water plants, large amounts of silt, turbid water, and its disagreeable smell and taste. The degradation of water is precipitated by anthropogenic activities (deposition of municipal sewage and agricultural contaminations such as fertilisers). The index of increasing eutrophication is a decrease in the concentration of oxygen in the water, as well as an increasing amount of various forms of nitrogen and phosphorus and a considerable increase of biomass. An activated growth of algae in the water proves the existence of eutrophication, which reduces the amount of solar energy penetrating deeper into the water and deteriorates the intensity of photosynthesis. This causes the concentration of oxygen in the water to be decreased, which results in fish perishing and anaerobic decomposition leading to the formation of methane and sulphuric compounds.

Plants growing on soils containing a large amount of nitrogen compounds are more susceptible to plant diseases. Nitrification of the environment also leads to an increased content of nitrates in underground water due to washing out. The growth of the population of algae in the water may cause toxic contamination, particularly when the algae appear in reservoirs feeding the water-pipe network.

Greenhouse effect

The greenhouse effect consists in retaining the energy of solar radiation in a space enclosed by panes as selective partitions. A similar role is played by the atmosphere due to its content of so-called greenhouse gases, viz., CO₂, CH₄, O₃, N₂O, chlorofluorocarbon compounds (e.g. CF₂Cl₂, CFC₃), SF₆ and steam. Greenhouses gases permit short-wave solar radiation to penetrate the atmosphere and heat the surface of the Earth, but they absorb long-wave infrared radiation emitted by the Earth. This may in future contribute to an increase in temperature of the atmosphere and the danger of the melting of ice caps. The greenhouse effect is due to human activities, mostly influenced by CO₂ emissions (so-called anthropogenic CO₂). It has been estimated that a doubled concentration of CO₂, when compared with its present concentration, may increase the average temperature of the atmosphere by 3 K, which again may result in a rise in the level of the oceans by 1.5 metres.

The greenhouse effect has been predicted since nearly the end of the nineteenth century, first by the Swedish physico-chemist Arrhenius in whose opinion an increase in the temperature of the atmosphere depends on its share of CO₂. His predictions have been confirmed by recent drillings of antarctic and arectic ice, which permitted investigations of the distribution of CO₂ in the atmosphere in the course of the past 160,000 years. The curve of changes in the atmospheric temperature, compared with the distribution of CO₂ concentration, has proved that there is a distinct correlation between the share of CO₂ and the temperature of the atmosphere [22].

A classic example of the greenhouse effect occurs on the planet Venus, the surface temperature of which amounts to about 500° C. Although this planet is closer to the Sun than the Earth, such a high temperature results from the greenhouse effect because the atmosphere of Venus is a mixture of CO₂ and CH₄.

The predicted results of the greenhouse effect are:

- the area between the tropics will change to deserts,
- the level of the oceans is increasing.

The following ways to prevent the greenhouse effect may be distinguished:

- economic management of energy,
- substituting coal by hydrocarbon fuels,
- a higher share of nuclear energy,
- a higher share of renewable energy resources,
- less deforestation,
- CO₂ capture and storage.

Reduction of the ozone layer (ozone depletion)

The ozone layer protects living organisms on the Earth against excessive ultraviolet solar radiation. The ozone layer is reduced due to the emission of chemical compounds containing chlorine. In 1974 Molina and Rowland presented for the first time the theory that chlorine contained in chlorofluorocarbons may reduce the ozone layer.

Chlorofluorocarbon compounds are applied in cooling and air-conditioning units, in the production of insulating foam materials, and in fire extinguishers. Characteristic features of these compounds are their chemical stability, non-toxicity and non-combustibility. If these compounds get into the atmosphere, they shift upwards to the higher layers. Affected by ultraviolet solar radiation, they educe chlorine radicals which react with ozone and decrease it. The mechanism for reducing the ozone layer proceeds as follows. Influenced by solar radiation, chlorofluorocarbon compounds decay releasing the chlorine atom which breaks O_3 into O_2 and O . The oxygen atom O bonds with Cl forming ClO which again decays due to solar radiation, and the atom Cl attacks the next particle O_3 . Accordingly, the ozone layer in the atmosphere becomes thinner and does not provide any protection against ultraviolet radiation (leading to carcinogenic effects, cataracts and deterioration of the eye's lens).

Eco-indicators

One of the first methods of quantifying ecological damages is the method known as Eco-indicator 99, replacing ECO-indicator 95, which reduces the categories of effects to three kinds of damages:

- hazard to human health (Disability Adjusted Life Years – DALY) – shortening human life due to noxious effects,
- damages to the quality of ecosystems (Potentially Disappeared Fraction – PDF) – the share of species dying out in a given region in the course of a year due to anthropogenic effects on the environment,
- depletion of natural resources.

8.4. Complex buildings as an object of LCA

Civil engineering as a whole, including the construction and exploitation of complex buildings, is a part of the economy, besides industry, which involves a considerable burden on the environment. This is the case in various stages of building activities, viz. [4, 2]:

- extraction of mineral raw materials and production of building materials,
- construction of buildings,
- demolition and recycling of the building materials.

The extraction of mineral raw materials and their transport, followed by the production of building materials, are loaded by the consumption of energy carriers, water and materials, and the removal of technological sewage, solid wastes and noxious gaseous emissions [3, 10]. Building materials are characterised by special properties such as heat transfer coefficient, porosity, strength, density, dimensions and so on. Building materials with comparable properties and the same qualities may differ in their amount of noxious emissions during production, depending on the applied techniques [12].

During the construction of buildings, negative effects on the environment are connected with the preparation of the site, the construction of access roads and provisional buildings, and the necessity of storing building materials and elements. In the course of construction additional nuisances occur, such as noise, vibrations, deformation of the landscape, disturbance of the underground water level, and earth removal. Building activities are strictly connected with the consumption of energy carriers (diesel oil, electricity and so on). During the process construction of buildings, the main elements (i.e. walls, ceilings and foundations) are made of materials meeting the criteria of strength and thermal requirements, but they differ in their environmental loading, which influences the final environmental loading of the element constructed on the site. Therefore physically similar complex buildings may differ from the viewpoint of their final ecological balance.

The environment is particularly affected in the phase of exploitation of a complex building. In European conditions this phase may even last 100 years. The capacity of installations for heating, ventilation, air-conditioning, water supply and so on depends on the properties of the complex building determined in the design and construction phases by the choice of the proper materials for shaping the multilayer partitions.

The demolition phase is also connected with the consumption of energy. Moreover, materials remaining after the demolition which cannot be recycled must be gathered and removed. Some of these may be recycled and again used.

Civil engineering which satisfies sustainable development should in all stages of the life cycle aim at a minimisation of energy consumption, taking into account, however, the

criterion of quality-of-life. The share of civil engineering in the consumption of final energy in countries with moderate climatic conditions amounts to about 40 per cent, dominated by the consumption of energy in the phase of exploitation. The main share of that (about 90 per cent) is due to heating, ventilation, air-conditioning and hot tap water preparation. Feeding the electrical equipment and lighting constitute the remaining 10 per cent of final energy consumption [17, 18].

In the case of complex buildings the product system is understood to be the system of the building comprising the phase of manufacturing the products and building materials, the phase of construction, and the phase of utilisation of the complex buildings determined by the duration of economically justified exploitation, in the course of which the features of utilisation meet the requirements of the “law of civil engineering”. Usually, this is the time up to the first general overhaul (20 to 25 years), because while constructing the complex buildings it is difficult to predict the development of building techniques and the way of producing building materials influencing the ecological balance of a building.

As a functional unit in LCA concerning housing, the building is frequently assumed. Nevertheless, additional functional units are also assumed; for example, mass unit (kg), volume (cbm) or surface area (sqm) in the phase of the production of building materials. In the case of the building as the functional unit, the volume (cbm of foundations) or surface area (sqm of external walls) is assumed, and in the phase of utilisation the usable floor area (sqm) is assumed.

The input to the product system (complex building) is the amount of materials and energy used [14, 15]. The output is the amount of emissions which are a hazard to the environment. In the case of complex buildings in which the LCI of energy management is very complex, input-output analysis may be applied. This concerns both the energy and materials balance and emissions leaving the system.

During the LCI assessment the effect of complex buildings on the environment and the indices of the categories are determined [19, 20]. According to the method Impact 2002+, 14 categories of the “midpoint” type have been distinguished, to which adequate substances of reference (SOR) have been assigned, viz. [3]:

1. toxic impact on the health - SOR kg_{eq} vinyl chloride,
2. impeded breathing - SOR kg_{eq} PM 2.5,
3. ionising radiation - SOR kg_{eq} C14,
4. reduction of the ozone layer - SOR kg_{eq} CFC-11,
5. photochemical smog - SOR kg_{eq} ethylene,

6. toxic effects on the water environment - SOR kg_{eq} triethylene glycol,
7. toxic effects on the terrestrial environment - SOR kg_{eq} triethylene glycol,
8. acidification of the terrestrial environment - SOR kg_{eq} SO_2 ,
9. acidification of the water environment - SOR kg_{eq} SO_2 ,
10. eutrophication - SOR kg_{eq} PO_4^3 ,
11. land use - SOR m^2 terrain/year,
12. greenhouse effect - SOR kg_{eq} CO_2 ,
13. depletion of non-renewable energy resources - SOR MJ of non-renewable primary energy,
14. depletion of other natural resources - SOR MJ of non-renewable primary energy.

The first five midpoint categories form the “endpoint” category “human health”, denoted by the index DALY (Disability Adjusted Life Years) taking into account both the death rate, as well as increased morbidity. The next six midpoint categories (six to 11) form the endpoint category “quality of the system”, denoted by the index PDF (Potentially Disappeared Fraction), which takes into account “the decline of species”. The twelfth midpoint category is at the same time the endpoint category “change in the climate”. The last two midpoint categories are the endpoint category “depletion of natural resources”. As far as other resources are concerned, besides primary energy of fuels, the index denotes additional consumption of energy for extracting raw materials in future due to the decrease of their concentration in the lithosphere.

In the stage “Interpretation” those phases of the lifetime of complex buildings are denoted which generate the strongest hazard for the environment. Simultaneously, ways to reduce negative influences on the environment are determined for both the phase of construction (application of building materials with a less environmental loading) and the phase of exploitation (e.g. the application of low-exergy heating systems). The last element of the “Interpretation” stage is the report of investigations.

Among methods for assessing the effect of complex buildings on the environment the British system BREEAM (Building Research Environmental Assessment Method) and the computer code ENVEST are best known.

8.5. Example of LCA of a case-study building using dedicated software

This example of LCA using the ENVEST program concerns the configuration of the case-study building, described in Chapter 7, during its life cycle. ENVEST uses a UK database of

LCA information concerning energy carriers, materials and elements such as walls or roofs. Therefore the calculated influence of that configuration of the office building on the global environment may be different in other countries.

8.5.1. Description of ENVEST software

ENVEST is a UK software for evaluating environmental impacts in the life cycle of complex buildings. This software considers many elements which have the most influence on the environmental impact of a building. The different environmental effects may be calculated by applying different materials for the construction of the building. Also the environmental impact of various strategies of heating, cooling and exploiting a building may be assessed. ENVEST analyses the environmental impact of the following aspects [8, 9]:

- consumption of materials in the construction phase of a building
- energy and other resources consumed over the lifetime of a building.

Environmental impacts of complex buildings may be considered from the viewpoint of many issues; for example, CO₂ emissions, extraction of raw materials, ozone depletion, and the generation of noxious substances. Each environmental issue is quantified by using its own value. For example, CO₂ emissions are measured in tons, while primary energy consumption is measured in GJ. Therefore it is hard to compare their impact on different environmental issues. This is why each environmental impact should be measured with the same scale. Building Research and Consultancy propose a scale which is the impacts of a typical UK citizen. All environmental impacts are measured using a single-point scale called Ecopoints, allowing a comparison of different solutions in buildings. The UK Ecopoint scale is a measure of the overall environmental building impact covering the following issues [11]:

- climate change,
- depletion of fossil fuel,
- depletion of the ozone layer,
- toxicity to air,
- toxicity to water,
- waste disposal,
- extraction of water,
- deposition of acid,
- ecotoxicity,

- eutrophication,
- smog,
- extraction of raw materials.

Exemplary data of cumulative emissions within the life cycle, which ENVEST uses for calculations, are shown in Table 8.1. UK Ecopoints are evaluated by taking into account each issue, calculated by multiplying the normalised impact with its percentage weighting. More Ecopoints show a higher environmental impact. One Ecopoint is equal to any (but not all) of the following forms of energy and materials [11]:

- 320 kWh electricity,
- 83 m³ water: enough to fill 1,000 baths,
- 65 miles by an articulated truck,
- landfilling 1.3 t of waste,
- manufacturing 3/4 t brick (250 bricks).

Table 8.1. Example values of cumulative emissions over life cycle which are used by ENVEST program [11]

Approved environmental profile		
BRE		
Characterised & Normalised data for:		Manufacture of 1 tonne Concrete Roof Tiles
		Quality of Data
		Start Date
		End Date
		Source of Data
		Geography
		Representativeness
		LCA Methodology
		Allocation
		Date of Data Entry
		Boundary
		Comments
Issues	Units	Characterised Data
Climate Change	kgCO ₂ eq (100yr)	270
Acid Deposition	kgSO ₂ eq	2.2
Ozone Depletion	kgCFC11 eq	0.000001
Pollution to Air: Human Toxicity	kg.tox	3.3
Pollution to Air: Low Level Ozone Creation	kg ethene eq (POCP)	0.076
Fossil Fuel Depletion and Extraction	toe	0.048
Pollution to Water: Human Toxicity	kg.tox	0.00000058
Pollution to Water: Ecotoxicity	m3 tox	1.1
Pollution to Water: Eutrophication	kg.PO ₄ eq.	0.18
Minerals Extraction	tonnes	1
Water Extraction	litres	1500
Waste Disposal	tonnes	0.11
Transport Pollution & Congestion: Freight	tonne.km	260
Issues	One UK Citizen	Normalised Data
Climate Change	12270 kgCO ₂ eq (100yr)	0.022
Acid Deposition	58.88 kgSO ₂ eq	0.037
Ozone Depletion	0.28595 kgCFC11 eq	0
Pollution to Air: Human Toxicity	90.7 kg.tox	0.036
Pollution to Air: Low Level Ozone Creation	32.23 kg ethene eq (POCP)	0.0024
Fossil Fuel Depletion and Extraction	4.085 toe	0.012
Pollution to Water: Human Toxicity	0.02746 kg.tox	0.000021
Pollution to Water: Ecotoxicity	837600 m3 tox	0.0000013
Pollution to Water: Eutrophication	8.006 kg.PO ₄ eq.	0.022
Minerals Extraction	5.04 tonnes	0.2
Water Extraction	417600 litres	0.0036
Waste Disposal	7.194 tonnes	0.015
Transport Pollution & Congestion: Freight	4140.84 tonne.km	0.062
Primary Energy	GJ	2.6

The environmental impacts may be evaluated per square metre of gross floor area of a building. Using this tool, it is possible to compare the results concerning the building under consideration with any other building previously entered. The software includes a database of most building materials. The calculating model of this program is based on a sensitivity analysis. Figure 8.5 presents a screen of the ENVEST software.

The software allows optimal (from the ecological point of view) building services (e.g. heating, cooling, lighting, hot water system) to be chosen. By means of this program we can graphically analyse the life cycle environmental impact of the building. Envest presents life cycle performances of a building by charts (Fig. 8.5).

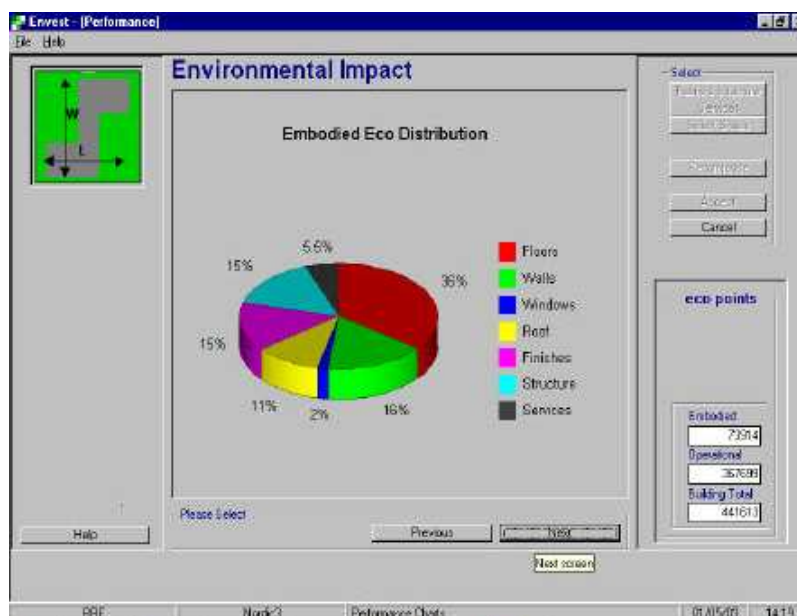


Fig. 8.5. Screen of ENVEST software

8.5.2. Example of calculations

All calculations have been made for the configuration of the case-study building over its life cycle using the ENVEST program. Table 8.2 presents the specification of aspects of the case-study building considered in the analysis.

Table 8.2 Specification of aspects of the case-study building considered in the analysis

Input values to calculations in ENVEST program		
Building data		
Building type:	-	Office
Building shape:	-	S-Shape.
Operational life:	-	50 Years
Soil type:	-	Firm clay
Occupancy:	-	20 m ² / person
Cellular space:	-	60% (0 if open plan)
Window grouping:	-	Grouped in rows
Building is air conditioned		
Building has catering facilities		
Main dimensions		
Length	-	80m
Width	-	50m
Number of storeys	-	7
Storey height	-	3.5m
Glazing Area		
North	-	20%
South	-	20%
East	-	40%
West	-	40%
Areas of building fabrics		
Ground floor:	-	2750m ²
Upper floor:	-	16500m ²
External walls:	-	4606m ²
Windows:	-	1764m ²
Roofs:	-	2750m ²
Internal walls:	-	11165m ²
Perimeter:	-	260m

Using the ENVEST program the overall number of Ecopoints generated by structural elements and services has been calculated. Results of these calculations are shown in Table 8.3.

Table 8.3. Results of calculations – overall number of Ecopoints generated by structural elements and services

Results of calculations		
Building fabrics		
Floors:		
Ground floor:	6501	Ecopoints
Upper floors:	27216	Ecopoints
Walls		
External walls:	9972	Ecopoints
Internal walls:	4330	Ecopoints
Windows		
Windows:	1886	Ecopoints
Roofs		
Structure:	6199	Ecopoints
Covering:	4612	Ecopoints
Finishes		
Floor:	11610	Ecopoints
Wall:	5240	Ecopoints
Ceiling:	2087	Ecopoints
Structures		
Superstructure:	13931	Ecopoints
Substructure:	1458	Ecopoints
Services embodied ecopoints	4690	Ecopoints
Total embodied:	99732	Ecopoints
Services Operational		
Heating:	150412	Ecopoints
Lighting:	134441	Ecopoints
Ventilation:	80416	Ecopoints
Refrigeration:	74990	Ecopoints
Water (including water heating):	11180	Ecopoints
Lifts:	1033	Ecopoints
Office equipment:	71173	Ecopoints
Catering:	48690	Ecopoints
Other:	33893	Ecopoints
Total services operational:	606228	Ecopoints
Building total:	705960	Ecopoints.

Calculations show that the main influence of that configuration of the building on the environment is connected with its operation. Figure 8.6 shows that the overall environmental impact connected with the construction, renovation and utilisation encompasses only 14 per cent of all Ecopoints generated by the building.

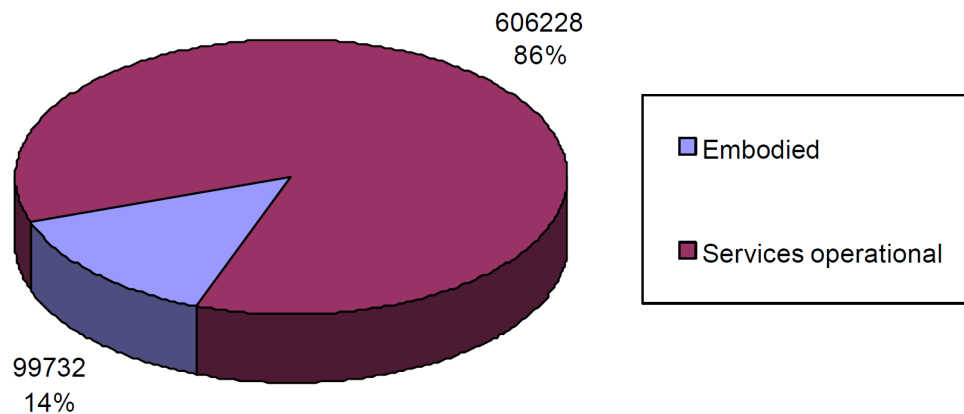


Fig. 8.6. Results of calculations – balance between operational and embodied Ecopoints

ENVEST allows the number of Ecopoints generated by different structural elements of the construction of the building within its life cycle to be calculated. Results are shown in Figure 8.7. As we can see in this chart, manufacturing the floors, walls and finishes of the building has the most environmental impact.

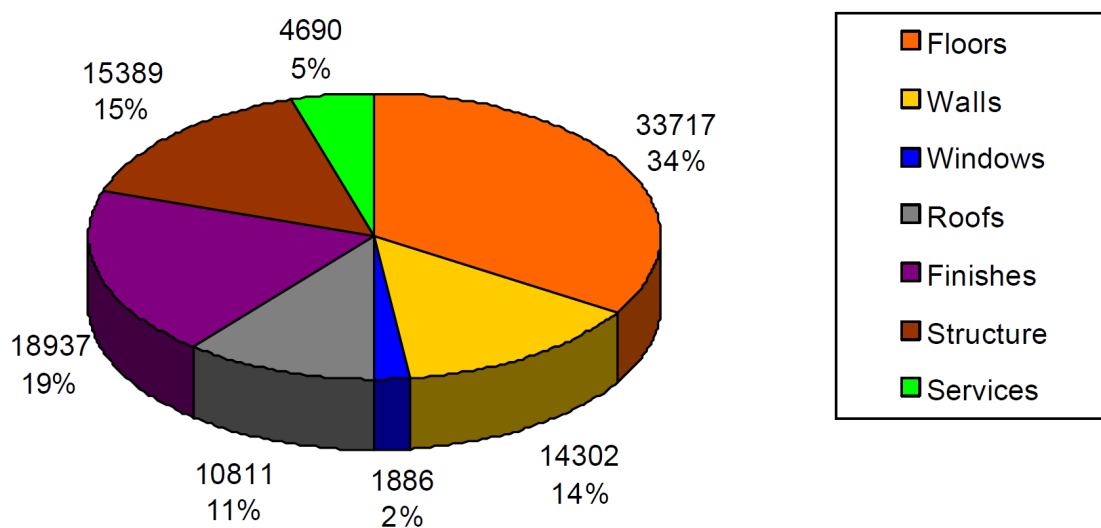


Fig. 8.7. Results of calculations – balance of Ecopoints for different structural elements of the building

Figure 8.8 shows the balance of Ecopoints generated by all services in the building. The heating system generates the highest environmental impact (about 25 per cent of all the Ecopoints) generated by all services. Lighting also exerts a significant influence on the whole balance of Ecopoints (22 per cent).

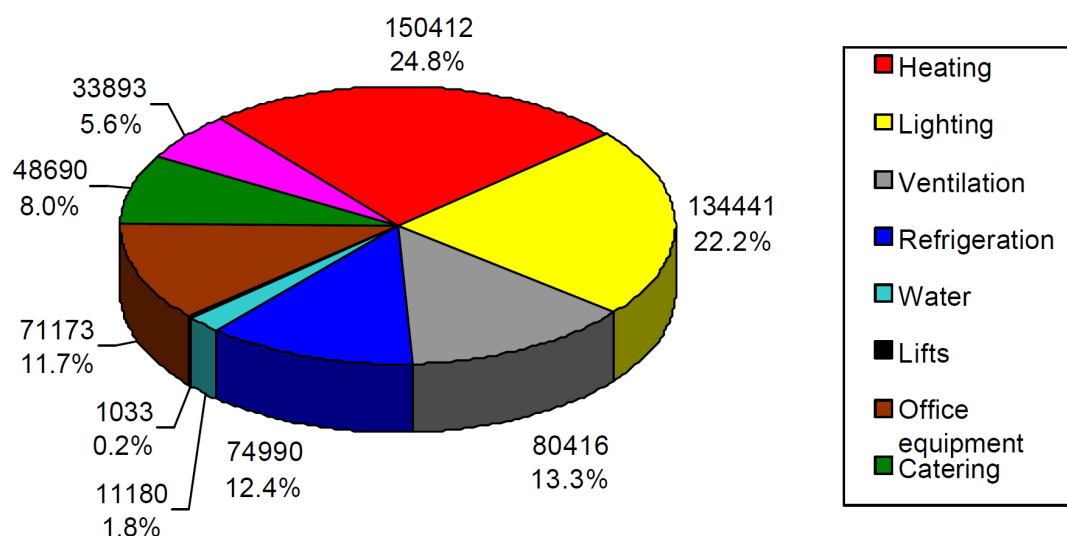


Fig. 8.8. Results of calculations – balance of Ecopoints for different services of the building

For the configuration of the case-study building simulations show that its operation causes the most environmental impact (86 per cent of all Ecopoints). The balance of Ecopoints generated by different services shows that the heating system exerts the most influence on the environment. The analysis of the structural elements shows that manufacturing the floors, walls and finishes of the building has the most environmental impact (respectively 34 per cent, 14 per cent and 19 per cent of all Ecopoints generated by the construction).

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Chapter 9

CHOICE OF THE STRUCTURE OF THE ENERGY SYSTEM OF COMPLEX BUILDINGS IN THE COURSE OF PRELIMINARY DESIGN

Traditional methods for choosing the structure of the energy management of complex buildings are based on the heuristic knowledge of designers, and as such they are restricted only to analyses of a few variants. Nowadays this is insufficient due to the permanently growing amount of technical and economic information about new techniques in the production of electricity, heat and cooling agents. This is in so far important that errors in the choice of the structure may cause not only unjustifiably high expenditures of investment but also higher expenditures of exploitation.

In order to avoid these errors, systems approach should be applied permitting to analyse all the possible justifiable variants of energy management of complex buildings. In the systems approach to choosing the optimal structure of the energy management of complex buildings the hierarchical feature of large energy systems and the input-output analysis should be applied.

As in the case of the traditional design method, the first stage ought to be the preparation of the scenario for the predicated energy management of a concrete complex buildings, taking into account its specific characteristics (in a supermarket, for instance, only hot water is used as a heat carrier, whereas in a hospital also steam is required as a high-temperature heat carrier). Such a scenario serves to set up a general specification of energy carriers comprising both energy carriers produced in complex buildings and those supplied from outside (e.g., fuels and raw water). Besides this general specification, a list of energy facilities which may be applied in the designed energy management of complex buildings should also be set up based on this scenario.

This then serves to form the matrix of the projects and subsets of designs, from which the variants of energy management of complex buildings are derived. To each variant corresponds a calculation diagram of energy management and a binary input-output matrix. Later on, this matrix is subjected to structural analysis resulting finally in a matrix with a minimum number of non-zero elements below the main diagonal. In this way the number of feedback interconnections is reduced to a minimum.

The mathematical optimisation model for choosing the structure of energy management of complex buildings is based on the decomposition of the global optimisation

task. Lagrange's method of decomposition is applied. This indicates that the coordination procedure is a matrix method of calculating the unit costs of energy carriers.

The descriptive model of this system method has been applied in the case of a typical office building, and the optimisation model was applied in the choice of the optimal energy management structure of an industrial-urban complex. In large urban districts energy subsystems may frequently serve both industrial consumers and complex buildings (e.g., sports and recreation centres).

9.1. Systems approach to the preliminary design of the energy management of complex buildings

In designing the following three phases may be distinguished:

- feasibility study of the design for the purpose of choosing a subset of useful solutions from a set of probably correct solutions, taking into account the possibility of realising them technically and the financial possibilities,
- preliminary design consisting in the choice of the optimal variant,
- detailed design aimed at providing the technical description of the optimal variant of the designed energy management system of the complex buildings.

In the course of preliminary design the optimal structure of energy management for complex buildings is chosen. The energy management structure is to be understood as a set of the main energy installations and engines determined by the power ratings and their number, as well as the configurations of their interconnections [3,4]. The set of possible variants of the energy management structure of complex buildings is abundant due to the large variety of elements (energy installations and engines) constituting the energy subsystem, numerous variants of thermodynamic parameters characterising these elements, as well as numerous possible combinations of interconnections of these elements. The task of the designer is to find those variants, to check the technical possibilities of their realisation, assessing each of them from the economic point of view, and by comparing them choose the optimal one. This is the aim of the preliminary design. The dimension of the task of choosing the optimal structure grows much more, if the uncertainty of the input data is taken into account. Therefore, in the phase of preliminary design a systems analysis is indispensable.

The choice of the energy management structure of complex buildings plays an important role in the process of designing due to the fact that the building sector is one of the

main consumers of energy [2,9,13]. The quality of final design depends on the technical solutions (kind of technology and equipment) assumed in that stage. Errors in the choice of the structure greatly affect the excess of capital investments and also the incorrect functioning of the designed energy subsystem. Traditionally, the most often applied method for choosing the energy management structure comprises the elaboration of several variants and the choice of the best one from among them. This is a heuristic approach based on hitherto gathered experience of designers. Nowadays this traditional approach has proven to be insufficient due to the continuous development of technology requiring new solutions, as well as the permanently growing amount of technical-economic information which ought to be utilized in designing [11].

The choice of the energy management structure of complex buildings should be based on a systematic review of all admissible structures. This requires the application of systems analysis [8]. The systems approach is to be understood as a way of solving problems in which the processes are treated to be complex from the point of view of internal and external interdependences [14].

Up-to-date designing applying systems analysis, comprises the following modules [7]:

- introduction of design data,
- search for information,
- mathematical modelling and optimisation,
- software,
- automatic preparation of documentation.

The module of the introduction of data permits the computer store to be provided with information concerning the designed energy subsystem (e.g., calculation diagram of the energy management system). The module of searching for information contains, for instance, a series of types of machines and other equipment to form the data base.

Modelling and optimisation comprise algorithmic and functional modules. The former is a procedure for calculating the designed element of the energy management system of complex buildings. Functional modules constitute organisational units of the subsystem of modelling and optimisation, by means of which new variants of the energy management system can be obtained. The algorithmic module is formulated in compliance with principles obligatory in system engineering and consist of the following stages:

- formulation of the problem,

- elaboration of a descriptive and optimising mathematical model,
- solution by means of the model,
- verification of the model and the obtained solution,
- control of the solution,
- practical application of the solution.

The module of modelling and optimisation allows the technique of simulation, to be practically applied, providing the following advantages:

- the possibility of checking a larger number of variables than in direct investigations,
- lower costs and a shorter duration of investigations,
- the possibility of attaining and checking conditions which do not yet exist in reality.

The structure of the energy subsystem presented as a calculation diagram, oriented graph or binary matrix of interbranch connections illustrates how the engines and energy installations are connected without presenting their physical form. This serves to describe the energy subsystem qualitatively. Therefore it is often called a topological structure.

The topological structure is determined in the course of preliminary designing concerning each variant of the energy subsystem analysed by the designer. Further on the quantitative characteristics are determined for both the systems of machines and energy equipment in the respective branches and their interbranch connections. These are first of all the power rating and capacity of the engines and energy installations and their number, as well as the coefficients of consumption and by-production of energy carriers. In this stage of preliminary design for each variant of the energy subsystem, the specifications of the systems of machines and equipment are determined. Next, the optimal technical structure is chosen.

The choice of the structure of the energy subsystem, being the aim of the preliminary design, is therefore the optimal task. As the task of optimisation is a complex one, due to the variety of algorithms of the choice of equipment for the respective energy carriers, the global optimisation task must be decomposed [10]. For this purpose the hierarchical feature of the energy subsystem is helpful. When optimising the respective branches, the power ratings of engines and energy installations are determined and also the nominal flux of external supplies of energy carriers (mainly fuels). Therefore knowledge of the duration curves for each energy carrier and the technical coefficients of consumption and by-production of energy carriers is indispensable. These coefficients depend both on the value of the power rating and the load. Thus, plotting the duration curves, the determination of the coefficients of consumption and

by-production of energy carriers, and the proper choice of power ratings, are interdependent tasks, solved iteratively [17].

9.2. Choice of the variants of energy management of complex buildings

The procedure for choosing the adequate structure of the energy management of complex buildings has been worked out based on the input-output model concerning the interbranch flow of energy carriers. The choice of this structure in the course of preliminary design consists in the formation of an optimal set of energy machines and equipment and the determination of interconnections between them resulting from the flows of energy carriers. First of all available techniques for producing energy carriers must be chosen, based on which the scenarios of energy management are developed for the given subsystem of energy consumers. The scenario is a verbal description of the method for realising the energy management concerning the complex buildings under consideration characterised by the vector of the demand for energy carriers covering the need of the subsystem of consumers.

The next step is to set up a universal specification of energy carriers comprising the main production of energy carriers, the by-production, and energy supplies from outside. This universal specification of energy carriers contains energy carriers, the production of which has to cover the demand of the subsystem of consumers, taking also into account energy carriers produced as a result of interbranch connections in the energy subsystem. The energy carriers quoted in the universal specification may be divided into two groups [15]:

- energy carriers produced in the energy subsystem as main products,
- external energy supplies and energy carriers being by-products in the energy subsystem which do not supplement the main production and the supplementary external supplies.

The energy carriers in this universal specification are described by binary vectors defining whether the given energy carrier is a main product (vector $\mathbf{B}_G^b$) or is supplied from outside (vector $\mathbf{B}_D^b$) and whether it is consumed directly in the subsystem of consumers (vector $\mathbf{O}^b$) (Table 9.1).

Besides the universal specification of energy carriers consumed in complex buildings a data base is set up concerning the thermal, electrical and cooling techniques applied in these complex buildings (Table 9.2). This data base serves to determine the technical coefficients of the input-output matrix characteristic for the table of interbranch flows.

At this stage the structure of the energy subsystem may be presented in the form of a calculation diagram and a corresponding oriented graph. The structure of the energy subsystem can be also described by the binary matrix of interbranch connections [16, 23]. The binary matrix is used to set up a table of interbranch connections of energy carriers in complex buildings. This table serves as the basis for the mathematical model of the energy management balance of the complex buildings.

Each energy carrier which is a main product corresponds to the design topic, which is connected with a subset of technical solutions. A technical solution is to be understood as a set of engines and energy installations realising the production of the given energy carrier. One design topic corresponds to several technical solutions. The production of heat in complex buildings, for instance, can be realised in a cogeneration unit, heating water boilers or a modern fuel cell. The set of design topics and technical solutions can be presented best as a binary matrix Π (e.g., Table.9.3.). This matrix comprises all the design topics and technical solutions which predict certain energy equipment or the possibility of providing energy carriers from outside. The respective rows in the matrix correspond to a given technical solution and the columns to a given engine or energy installation.

Every technical solution is described by binary matrices of the connections $\mathbf{A}_p^b = [a_{p\,ij}^b]$ and $\mathbf{F}_p^b = [f_{p\,ij}^b]$, the elements of which are defined as follows:

$a_{p\,ij}^b = 1$ - if the i -th energy carrier is consumed in the p -th technical solution for the production of the j -th energy carrier,

$a_{p\,ij}^b = 0$ - the opposite of the former one,

$f_{p\,ij}^b = 1$ - if the i -th energy carrier is a by-product in the p -th technical solution for the production of the j -th energy carrier,

$f_{p\,ij}^b = 0$ - the opposite of the former one.

where:

$$p = 1, 2, \dots, m$$

$$i = 1, 2, \dots, n$$

$$j = 1, 2, \dots, n_g$$

m - number of technical solutions,

n - number of energy carriers in the universal specification,

n_g - number of energy carriers produced as main products.

If the technical solution contains a basic and a peak energy installation or engine, the binary matrices $\mathbf{A}_p^b$ and $\mathbf{F}_p^b$ are determined by summing up the binary matrices describing the consumption and by-production in the basic and peak ones, according to the principles of Boolean algebra [20]:

$$\mathbf{A}_p^b = \mathbf{A}_{pP}^b + \mathbf{A}_{pG}^b \quad (9.1)$$

$$\mathbf{F}_p^b = \mathbf{F}_{pP}^b + \mathbf{F}_{pG}^b \quad (9.2)$$

Based on the matrix $\mathbf{A}_p^b$ the binary matrix $\mathbf{Z}^b$ is formed describing the structure of the consumption of energy carriers in the set of technical solutions:

$$\mathbf{Z}^b = [\mathbf{A}_1^b \mathbf{I}_0, \dots, \mathbf{A}_p^b \mathbf{I}_0, \dots, \mathbf{A}_m^b \mathbf{I}_0] \quad (9.3)$$

where $\mathbf{I}_0$ denotes the column vector with n_g unit elements; the multiplication of the matrix $\mathbf{A}_p^b$ by the vector $\mathbf{I}_0$ is in accordance with Boolean algebra.

As mentioned above, to each design topic an energy carrier is assigned, produced as the main product. Choosing one technical solution from each design topic, a set of all realisable variants of the energy management structure is elaborated and then subjected to a further analysis in order to choose the optimal variant. The number of all possible variants of energy management amounts to:

$$N = \prod_{t=1}^s m_t \quad (9.4)$$

where:

t - running number of the design topic,

m_t - number of technical solutions in the t -th design topic,

s - number of design topics.

In order to find out all the possible variants of the energy management structure the binary column vector $\mathbf{W}_l^b$ is set up, which is defined as follows:

$w_{pl} = 1$ - if the p -th solution belongs to the l -th variant of the structure of energy management,

$w_{pl} = 0$ - the opposite of the former,

where $l = 1, 2, \dots, N$, denotes the running number of the variant of the structure of energy management of the complex buildings.

The principle of the formation of the vector $\mathbf{W}_i^b$ concerning each variant of energy management consists in assigning one technical solution to each design topic. The number of realisable variants of the energy management of complex buildings, determined in this way, is usually very high and a large number of the determined variants are economically a priori unjustified [6]. As an example may serve a variant in which electricity and heat are produced in several CHP units based on various technologies (e.g., a CHP unit with a piston combustion engine cooperating with a CHP unit based on a fuel cell). In this case there are two different cogeneration technologies. This does not exclude the so-called hybrid systems described in Chapter 4. In spite of the fact that the energy management of modern complex buildings is becoming more and more complex, the investor usually chooses only one kind of cogeneration technique. Although in modern complex buildings several parallelly operating CHP units are applied, they still work basing on the same technique. These remarks do not concern the production of energy carriers in basic and peak equipment. In order to exclude such cases (e.g., a combination of two different techniques of cogeneration) in further considerations they may be eliminated from the set of all variants of energy management applying the so-called criterion of technological compatibility. For this purpose the binary column vector $\mathbf{L}_h^b$ is formed determining that group of energy installations which produce the same energy carriers by means of different technologies. The elements of this vector are defined as follows:

$\mathbf{L}_{uh} = 1$ - if the u -th energy installation belongs to the h -th group of devices producing the same energy carriers applying different technologies,

$\mathbf{L}_{uh} = 0$ - the opposite of the former case.

In order to identify all the energy carriers produced together with other energy carriers in one common energy installation the binary column vector $\mathbf{M}_s^b$ is formulated. The elements of this vector are determined as follows:

$\mathbf{M}_{is} = 1$ - if the i -th energy carrier belongs to the s -th group of energy carriers produced together with other energy carriers in one common energy installation,

$\mathbf{M}_{is} = 0$ - the opposite of the former case.

Based on the vectors $\mathbf{L}_h^b$ and $\mathbf{M}_s^b$ all those variants of energy management are eliminated which do not satisfy the criterion of technological compatibility, verifying in this way the set of variants.

In spite of the verification of the variants by means of the vectors $\mathbf{L}_h^b$ and $\mathbf{M}_s^b$ the respective vectors $\mathbf{W}_l^b$ of the variants may include technical solutions not required to warrant cover the demands for energy carriers in the subsystem of consumers. For instance, replacing, an absorption refrigerator by a compression refrigerator, heat feeding the absorption aggregate is not required. In such cases unnecessary technical solutions are eliminated from the vectors of the variants of the structure of the energy management of complex buildings. For this purpose the matrix $\mathbf{Z}^b$ (Table 9.4) is in compliance with the principles of Boolean algebra multiplied by the vector $\mathbf{W}_l^b$ of the given variant, attaining in this way the vector $\mathbf{Y}_l^b$ which determines the demand for the respective energy carriers resulting merely from the needs of the energy subsystem in the given variant of the energy management. In the next step, according to Boolean algebra, the vector $\mathbf{O}^b$ is added to the vector $\mathbf{Y}_l^b$, expressing the demand for energy carriers in the subsystem of consumers. In this way the vector $\mathbf{X}_l^b$ is obtained defining which energy carriers are consumed in the given variant. The vector $\mathbf{X}_l^b$ is compared with the vector $\mathbf{W}_l^b$ of the considered variant, attaining information whether in this variant those energy carriers are taken into account which are neither applied in the energy subsystem nor in the subsystem of consumers. If the vector $\mathbf{X}_l^b$ includes a zero element for the given energy carrier and when simultaneously it results from the analysis of vector $\mathbf{W}_l^b$ that it comprises a technical solution connected with the production or supply of this energy carrier, this a technical solution should be excluded from the given variant.

The binary matrices $\mathbf{A}_p^b$, $\mathbf{A}_G^b$, $\mathbf{F}_p^b$, $\mathbf{F}_G^b$ of interconnections describing the structure of the energy management of complex buildings are determined based on the following relations [20]:

$$\mathbf{A}_p^b = \Phi_p^b \mathbf{W}_l^b, \quad (9.5)$$

$$\mathbf{A}_G^b = \Phi_G^b \mathbf{W}_l^b, \quad (9.6)$$

$$\mathbf{F}_p^b = \Psi_p^b \mathbf{W}_l^b, \quad (9.7)$$

$$\mathbf{F}_G^b = \Psi_G^b \mathbf{W}_l^b, \quad (9.8)$$

where:

$$\Phi_p^b = [\mathbf{A}_{1p}^b, \dots, \mathbf{A}_{pP}^b, \dots, \mathbf{A}_{mP}^b], \quad (9.9)$$

$$\Phi_G^b = [\mathbf{A}_{1G}^b, \dots, \mathbf{A}_{pG}^b, \dots, \mathbf{A}_{mG}^b], \quad (9.10)$$

$$\Psi_P^b = [\mathbf{F}_{1P}^b, \dots, \mathbf{F}_{pP}^b, \dots, \mathbf{F}_{mP}^b], \quad (9.11)$$

$$\Psi_G^b = [\mathbf{F}_{1G}^b, \dots, \mathbf{F}_{pG}^b, \dots, \mathbf{F}_{mG}^b]. \quad (9.12)$$

where the binary matrices of interbranch connections $\mathbf{A}_{pP}^b$, $\mathbf{A}_{pG}^b$, $\mathbf{F}_{pP}^b$, as well as $\mathbf{F}_{pG}^b$ being the data base, determine the structure of demands and the by-production of the energy carriers required for the respective design solutions concerning the basic and peak installations.

The input-output binary matrix $\mathbf{A}^b + \mathbf{F}^b$ is determined based on the relation:

$$\mathbf{A}^b + \mathbf{F}^b = \mathbf{A}_P^b + \mathbf{A}_G^b + \mathbf{F}_P^b + \mathbf{F}_G^b \quad (9.13)$$

The summation is in agreement with the principles of Boolean algebra.

9.3. Structural analysis of the binary input-output matrix

A structural analysis permits the degree of complexity of interconnections between the energy branches to be assessed and the input-output matrix to be transformed in order to obtain a structure of this matrix better adapted for further calculations. This means a transformation of the binary input-output matrix approximated to the upper triangular matrix as far as possible. This procedure is called minimisation of the number of non-zero elements below the main diagonal of the input-output matrix, because these elements determine the feedback loops which increase the complexity of numerical calculations [10]. The structural analysis is performed by means of the binary input-output matrix $(\mathbf{A}^b + \mathbf{F}^b)$.

The following characteristic stages of structural analysis can be distinguished:

- decomposition of the energy subsystem,
- separation of strongly coherent subsystems,
- sequence of balancing the energy branches.

Decomposition consists in the division of the energy management system of complex buildings into subsystems of a lower order, comprising the production of one energy carrier or a group of energy carriers. First of all, in the binary matrix $(\mathbf{A}^b + \mathbf{F}^b)$ the “output”, “centre” and “input” blocks are separated. Energy branches belonging to the output block do not influence other energy branches, but they themselves are affected by the energy subsystem. Energy carriers produced in branches belonging to this block are used only in the subsystem

of consumers. In the matrix $\mathbf{A}^b + \mathbf{F}^b$ the branches of the output block correspond to the zero rows. Energy branches belonging to the input block are not influenced by the energy subsystem, but they affect other energy branches. These branches are characterised by the fact that in them no other energy carriers are consumed. In the matrix $\mathbf{A}^b + \mathbf{F}^b$ the zero columns correspond to the branches belonging to this block. The remaining branches belonging to the centre block are characterised by interconnections resulting from the consumption and by-production of energy carriers. Feedback connections exist between the branches belonging to this group. The separation of these three mentioned groups of branches results in the division of the matrix $\mathbf{A}^b + \mathbf{F}^b$ into blocks. The division of energy branches into output, centre and input blocks provides the first approximation of the input-output matrix $(\mathbf{A}^b + \mathbf{F}^b)$ to its upper triangular form.

Further in the course of this structural analysis strongly coherent subsystems can be distinguished among the branches belonging to the centre block [1]. The set of branches is a strongly coherent subsystem if any given branch of this set is connected with every other branch of this set. Thus, the centre submatrix is transformed into a block matrix. Interconnections between branches belonging to various strongly coherent subsystems are series connections. Feedback connections exist only between branches belonging to the same strongly coherent subsystem. The transformation of the input-output matrix $(\mathbf{A}^b + \mathbf{F}^b)$ to the form of the upper triangular block containing the least number of elements situated below the main diagonal determines the sequence in the choice of the energy equipment.

In the case of already existing energy management systems, the matrix equation of the energy balance is usually solved by means of the inverse matrix $(\mathbf{I} - \mathbf{A} + \mathbf{F})^{-1}$. In the course of preliminary design, the values of the elements of the matrices $\mathbf{A}_G$, $\mathbf{A}_P$, $\mathbf{F}_G$, $\mathbf{F}_P$ are unknown. Thus, the set of balance equations of energy carriers is solved separately for each branch in the order determined by the structural analysis ensuring the best effectivity of calculations. And this is why the matrix $(\mathbf{A}^b + \mathbf{F}^b)$ should be transformed into a matrix most similar to the upper triangular matrix. For this purpose this sequence of branches in the submatrix concerning the strongly coherent system is to be chosen, so that the number of elements below the main diagonal of the matrix will be at a minimum.

In order to separate strongly coherent subsystems in the centre group, the following matrix has been determined:

$$\mathbf{C} = \sum_{s=1}^r (\mathbf{A}^b + \mathbf{F}^b)_c^s \quad (9.14)$$

where summing up of the successive powers of the matrix $(\mathbf{A}^b + \mathbf{F}^b)_c$ is continued until the condition is met, where for any $r \leq n_c$:

$$\sum_{s=1}^r (\mathbf{A}^b + \mathbf{F}^b)_c^s = \sum_{s=1}^{r+1} (\mathbf{A}^b + \mathbf{F}^b)_c^s = \dots = \sum_{s=1}^{n_c} (\mathbf{A}^b + \mathbf{F}^b)_c^s \quad (9.15)$$

where:

n_c the number of energy carriers belonging to the centre group,

$(\mathbf{A}^b + \mathbf{F}^b)_c$ - binary matrix of interconnections belonging to the centre block.

In Eqs. (9.14) and (9.15) the principles of Boolean algebra are obligatory.

Matrix $\mathbf{C}^b$ is defined as follows:

$c_{ij}^b = 1$ - if between the branches i and j of the centre block exist direct or indirect connections,

$c_{ij}^b = 0$ - the opposite of the former one.

The input-output matrix $(\mathbf{A}^b + \mathbf{F}^b)_c$ informs us whether direct connections between the branches (energy carriers) “ i ” and “ j ” do exist, whereas the matrix $\mathbf{C}^b$ also provides information about indirect connections between these branches realised by means of branches belonging to the centre block.

Next the matrix of intersection $\mathbf{W}$ is deduced from the equation:

$$\mathbf{W} = \mathbf{C} \cap \mathbf{C}^T$$

which may be defined as follows:

$w_{ij}^b = 1$ - if $c_{ij}^b = c_{ji}^b = 1$,

$w_{ij}^b = 0$ - the opposite of the former one.

The matrix $\mathbf{W}$ comprises non-zero elements only in the case when non-zero elements occur in the matrix $\mathbf{C}$ and matrix $\mathbf{C}^T$. In the matrix $\mathbf{W}$ one-sided connections are reduced to zero. The matrix $\mathbf{W}$ is a matrix with diagonally arranged blocks. The respective blocks along the main diagonal represent strongly coherent subsystems.

The transformation of the binary input-output matrix into the form of the upper triangular block matrix with a minimum number of elements below the main diagonal consists in an adequate arrangement of the rows and columns in the input-output matrix, applying for this

purpose the algorithms of the topological classification. This matrix determines the sequence of balancing the energy demands and the choice of energy engines and installations.

9.4. Mathematical optimisation model of the energy balance

The aim of preliminary design is to choose the optimal variants of the energy management system. The criterion of the energy management is the maximum of the annual economic effect of operation of complex buildings for which the structure of energy management has been chosen. In the case of the assumed demand for energy carriers in the subsystem of consumers of complex buildings this is reduced to a minimisation of the annual costs of operation of the energy subsystem. The objective function takes the following form according to Eqs. (3.19)-(3.21):

$$C_a = (\rho_P + \beta_P) \mathbf{I}_P + (\rho_G + \beta_G) \mathbf{I}_G + (\rho_{DG} + \beta_{DG}) \mathbf{I}_{DG} + \alpha_P \dot{\mathbf{P}}_n + \alpha_G \dot{\mathbf{G}}_n + \alpha_{DG} \dot{\mathbf{D}}_{Gn} + \varepsilon_P \mathbf{P} + \varepsilon_G \mathbf{G} + \varepsilon_{DG} \mathbf{D}_G + \varepsilon_G \mathbf{G} + \mathbf{k}_{DD} \mathbf{D}_D \Rightarrow \min \quad (9.17)$$

where:

C_a - total annual cost,

ρ - row vector of the annual capital recovery factor,

β - row vector of the rates of fixed costs dependent on the capital expenditure,

$\mathbf{I}$ - column vector of capital expenditure,

α - row vector of the indices of labour costs,

ε - row vector of the indices of exploitation costs including environment taxes; in the case of supplementary supplies also cost of purchase,

$\dot{\mathbf{P}}_n$ - column vector of the power rating of basic equipment,

$\dot{\mathbf{G}}_n$ - column vector of the power rating of peak equipment,

$\dot{\mathbf{D}}_{Gn}$ - column vector of nominal supplementary supplies from outside,

$\mathbf{P}$ - column vector of the annual production by basic equipment,

$\mathbf{G}$ - column vector of the annual production by peak equipment,

$\mathbf{D}_G$ - column vector of the annual supplementary supply of energy carriers,

$\mathbf{k}_{DD}$ - row vector of unit costs of energy carriers entirely supplied from outside,

$\mathbf{D}_D$ - column vector of annual supply of energy carriers entirely from outside

The indices “ P ”, “ G ”, “ DG ” and “ DD ” concern, respectively, the basic and peak parts of production supplementary supplies and energy carriers entirely supplied from outside.

The relations between the annual production G_i , P_i , D_i and power ratings $\dot{G}_{ni}$, $\dot{P}_{ni}$, $\dot{D}_{Gni}$ are:

$$\dot{G}_{ni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{G}_i(\tau) d\tau \quad (9.18)$$

$$\dot{P}_{ni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{P}_i(\tau) d\tau \quad (9.19)$$

$$\dot{D}_{Gni} = \frac{1}{\tau_n} \int_0^{\tau_0} \dot{D}_{Gi}(\tau) d\tau \quad (9.20)$$

where $G_i(\tau)$, $P_i(\tau)$ and $D_{Gi}(\tau)$ denote functions describing the duration curves and τ_n , τ_0 denote the annual duration of work with the power rating load and the annual duration of operation.

Decision variables are vectors of the power ratings $\dot{G}_n$, $\dot{P}_n$, $\dot{D}_{Gni}$. The vector of peak production G and basic production P , as well as the vector of external supplementary supplies D_G result from the choice of the optimal power rating and nominal capacities and also from the duration curves of the total demand for energy carriers (Fig. 9.1).

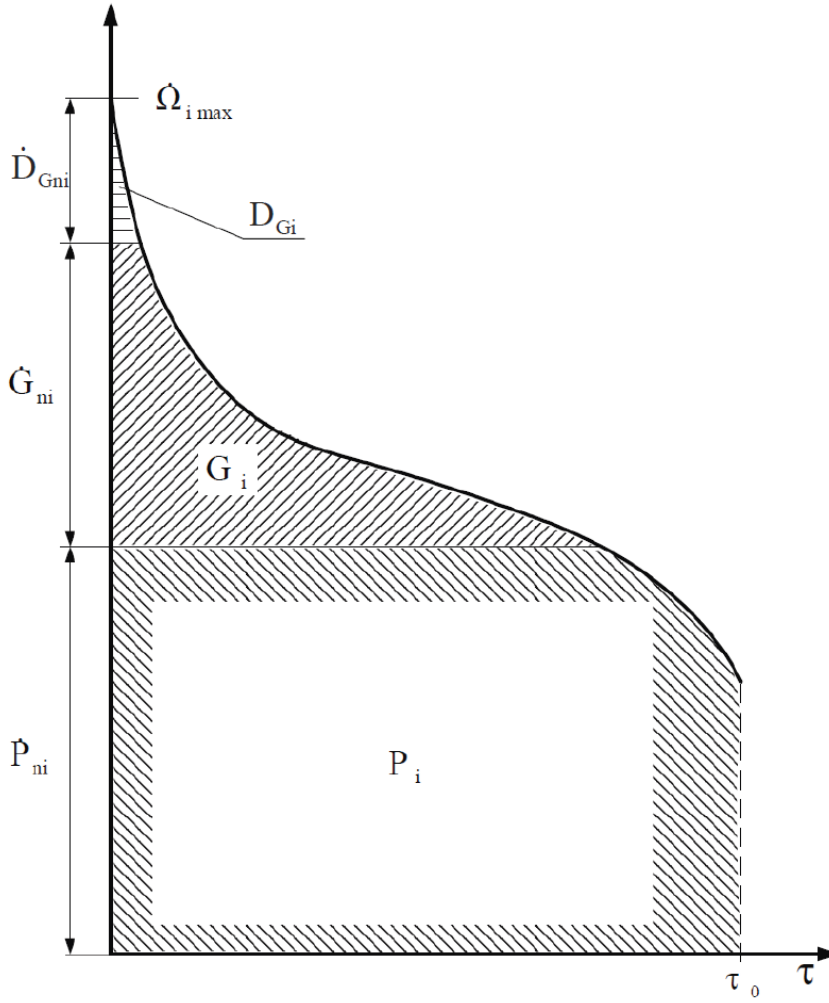


Fig. 9.1. Duration curve concerning annual demand for the „i-th” energy carrier

The global equality constraint is a matrix equation of the energy carriers balance quoted in Chapter 6 concerning the descriptive mathematical model. They are equality constraints in the optimisation task. Local constraints concerning the respective energy branches result from the maximum demand for each energy carrier and from the limitation of external supplies and capital expenditures, if required:

$$\dot{P}_{ni} + \dot{G}_{ni} + \dot{D}_{ni} \leq \dot{\Omega}_{i \max} \quad (9.21)$$

$$\dot{D}_{Gni} \leq \vartheta_{DGi} \text{ and } \dot{D}_{Dni} \leq \vartheta_{DDi} \quad (9.22)$$

$$I_{Pi} + I_{Gi} + I_{Di} \leq I_i \quad (9.23)$$

where:

$\dot{\Omega}_{i\max}$ - maximum demand for the i-th energy carrier,

ϑ_{DGi} - limit of external supplementary supplies of the i-th energy carrier,

$\dot{D}_{Dni}$ - nominal flux of the i-th energy carrier entirely supplied from outsider,

ϑ_{DDi} - limit of the i-th energy carriers entirely supplied from outside,

I_i - limit of capital expenditures concerning the i-th energy carriers.

In the case of external supplementary supplies capital expenditures and costs of exploitation have been taken into account connected with the change of thermodynamic parameters and distribution of external supplies. As far as energy carriers supplied entirely from outside are concerned it has been assumed that they are burdened only with the costs of their purchase.

9.5. Decomposition of the global optimisation task

In order to solve the global optimisation task (9.17) we must know the duration curves of the demand for each energy carrier, as well as the technical coefficients of consumption and by-production of energy carriers. These are determined based on the energy characteristics depending on both the power rating and the load of energy engine and equipment. Changes in the load are expressed by the duration curves, but in order to construct the duration curves the technical coefficients must be known. Thus, the construction of duration curves of the demand for energy carriers, the determination of the technical coefficients of consumption and by-production of energy carriers, the choice of the power ratings of machines and energy equipment, and also the nominal amount of supplies are mutually connected tasks. Their solution requires the decomposition of the global optimisation task. For this purpose Lagrange's method of decomposition is applied [10]. Taking into account the constraint equation (6.12) (Chapter 6) and disregarding the constant terms **B** and **C** which do not influence the result of optimisation, the objective function (9.17) takes the following form

$$\mathbf{L} = C_a + \lambda(\mathbf{A}_G \mathbf{G} + \mathbf{A}_p \mathbf{P} - \mathbf{G} - \mathbf{P} - \mathbf{F}_G \mathbf{G} - \mathbf{F}_p \mathbf{P} - \mathbf{D}_G) \quad (9.24)$$

where λ denotes the row vector of Lagrange multipliers.

The determination of the vector λ requires knowledge of the coordinating procedure warranting the compatibility of the local optimum of the respective branches with the global one. In order to determine this procedure in the analysis under consideration, the objective function is formulated concerning any j-th energy branch. An auxiliary balance diagram for the formulation of the objective function and further considerations is presented in Figure 9.2. The main and by-production are the useful results of the operation of this branch. Various unit costs of the production of both kinds of main production (basic and peak production) have been taken into account. Besides the quantities in the global objective function the expenditure in this case also comprises the costs of consumed energy carriers produced in other branches of the energy subsystem. In this case the average costs of the production of energy carriers in the energy subsystem are applied [21]. The external supplies (supplementing supplies – e.g., electricity, and only those from outside – e.g., fuel) are taken into account in C_{aj} . In this case the expenditure comprises fixed and variable costs connected with the preparation of the energy carrier supplied from outside to be used in the complex buildings (e.g., costs connected with the operation of the thermal centre). Figure 9.2. also presents the summing point for the determination of the average cost of the energy carrier [21].

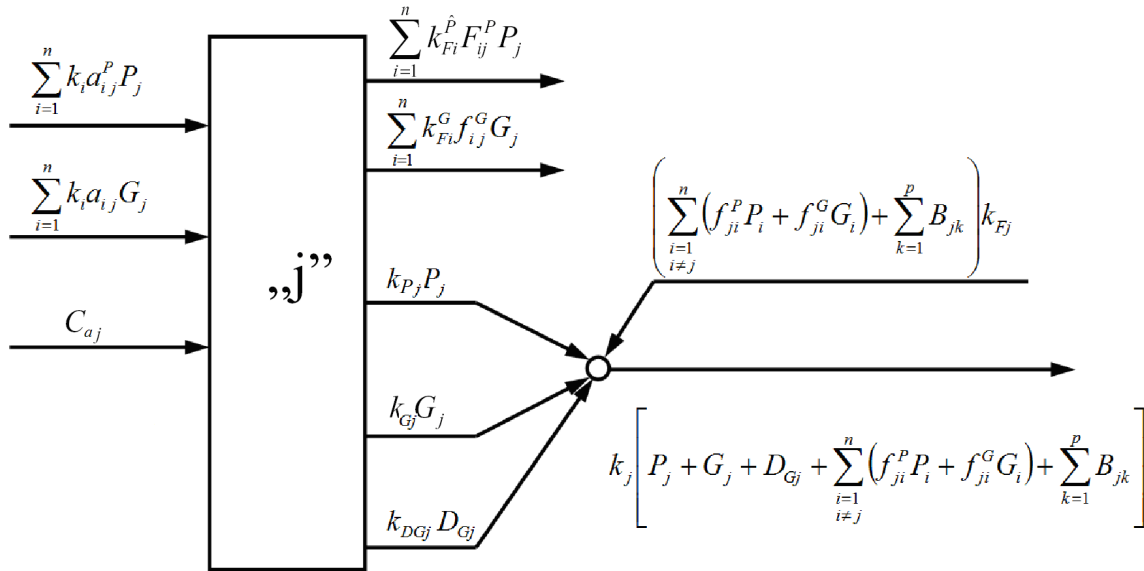


Fig. 9.2. Auxiliary diagram used for the formulation of the objective function of the energy branch

The objective function concerning the considered j-th branch of the energy subsystem is expressed as follows:

$$\phi = C_{aj} + \sum_{i=1}^n k_i (a_{ij}^P P_j + a_{ij}^G G_j) - \sum_{i=1}^n k_{Fi} f_{ij}^P P_j - \sum_{i=1}^n k_{Fi} f_{ij}^G G_j \Rightarrow \min \quad (9.25)$$

where:

$$\begin{aligned} C_{aj} = & (\rho_{Pj} + \beta_{Pj}) I_{Pj} + (\rho_{Gj} + \beta_{Gj}) I_{Gj} + (\rho_{DGj} + \beta_{DGj}) I_{DGj} + \alpha_{Pj} \dot{P}_{nj} + \alpha_{Gj} \dot{G}_{nj} + \alpha_{DGj} \dot{D}_{Gj} + \varepsilon_{Pj} G_j + \\ & + \varepsilon_{Gj} G_j + \varepsilon_{DGj} D_{Gj} + \sum_{l=n+1}^m k_{DDl} a_{lj}^{PD} P_j + \sum_{l=n+1}^m k_{DDl} a_{lj}^{GD} G_j \end{aligned} \quad (9.26)$$

where (both in Fig. 9.2 and Eqs. 9.25, 9.26):

C_{aj} - part of the objective function (9.17) concerning the j-th energy branch,

k_i - average unit cost of the i-th energy carrier,

k_{Pj} - unit cost of the basic part of production of the j-th energy carrier,

k_{Fj}, k_{Fi} - unit cost of the by-production of the j-th or i-th energy carrier,

k_{Gj} - unit cost of the peak part of production of the j-th energy carrier,

k_{DDl} - unit cost of energy carriers entirely supplied from outside.

The descriptions of remaining values in Eq.(9.26) correspond to descriptions of the respective vectors in Eq.(9.17). The indices “i” and “j” are applied in the denominations interchangeably.

The applied method of decomposition reduces the optimisation task to an iterative procedure [10]. In the successive iterative step on the upper level of the hierarchical scheme Lagrange’s multipliers are determined by an adequate coordinating procedure. Then based on the assumed values of Lagrange’s multipliers, every subsystem on the lower level of the hierarchical scheme is autonomously optimised [10]. In the case under consideration the level of the subsystem (energy branches) the power ratings of the basic and peak equipment are determined as well as the nominal quantities of supplies of energy carriers from outside (Fig. 9.3).

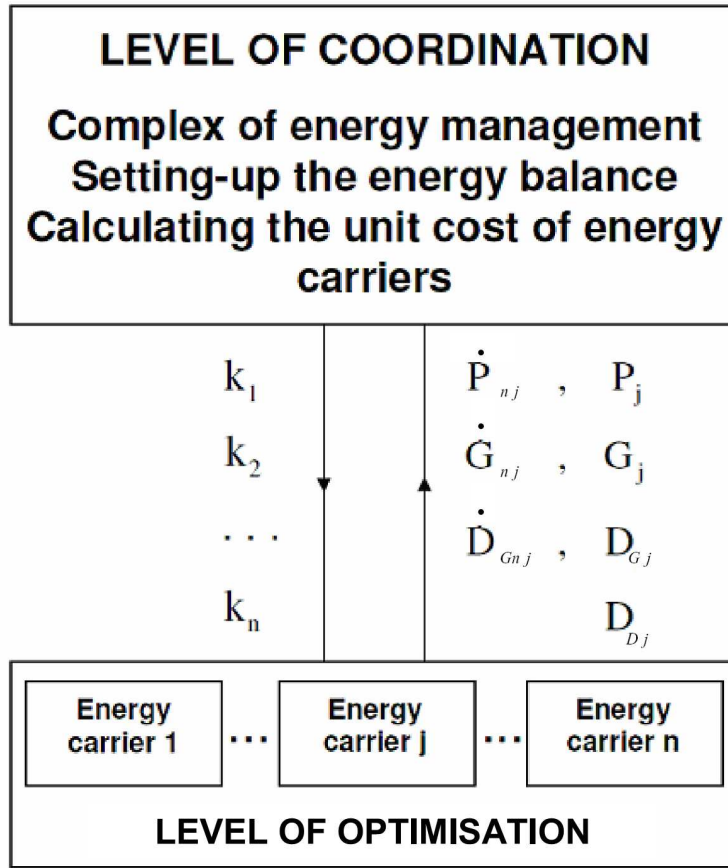


Fig. 9.3. Diagram of the Lagrange's method of the decomposition

In Eq. (9.25) concerning the objective function on the level of optimisation of the respective energy branch the cost k_i and k_{Fi} of energy carriers are fixed. The following terms are also fixed:

$$k_j(P_j + G_j + D_{Gj}) = \text{const} \quad (9.27)$$

$$(k_j - k_{Fj}) \sum_{i=1}^n (f_{ij}^P P_i + f_{ij}^G G_i) = \text{const} \quad (9.28)$$

The term (9.27) is constant, because in successive iteration the global demand for the energy carrier “j” is fixed. The division of the global demand for energy carriers between the energy produced in the energy management of complex buildings itself and the external supply is solved on the level of optimisation. The term (9.28) is also constant in the given iteration due to the summation with regard to “i”, except $i=j$. Hence, the terms (9.27) and (9.28) may be included in the objective function (9.25) without influencing the results of optimisation. After the summation of the objective function (9.25) for all the energy branches

considered on the level of optimisation with the additionally included terms (9.26) and (9.27) we obtain:

$$\begin{aligned} \sum_{j=1}^n \phi_j = & \sum_{j=1}^n C_{aj} + \sum_{j=1}^n \sum_{i=1}^n k_i (a_{ij}^P P_j + a_{ij}^G G_j) - \sum_{j=1}^n \sum_{i=1}^n k_{Fi} f_{ij}^P P_j - \sum_{j=1}^n \sum_{i=1}^n k_{Fi} f_{ij}^G G_j - \\ & - \sum_{j=1}^n k_j (P_j + G_j + D_{Gj}) - \sum_{j=1}^n k_j \sum_{i=1}^n (f_{ij}^P P_i + f_{ji}^G G_j) + \sum_{j=1}^n k_{Fi} \sum_{i=1}^n f_{ij}^P P_i + \sum_{j=1}^n k_{Fj} \sum_{i=1}^n f_{ji}^G G_j \end{aligned} \quad (9.29)$$

Reducing similar terms in Eq.(9.29) and using the matrix notation we obtain:

$$\sum_{j=1}^n \phi_j = C_a + \mathbf{k}^T (\mathbf{A}_G \mathbf{G} + \mathbf{A}_P \mathbf{P} - \mathbf{G} - \mathbf{P} - \mathbf{F}_G \mathbf{G} - \mathbf{F}_P \mathbf{P} - \mathbf{D}_G) \quad (9.30)$$

where $\mathbf{k}$ denotes the column vector of the average unit costs of energy carriers.

Comparing Eqs.(9.30), and (9.24), we can write:

$$L = \sum_{j=1}^n \phi_j \quad (9.31)$$

and

$$\boldsymbol{\lambda} = \mathbf{k}^T \quad (9.32)$$

Thus, the Lagrange multipliers are equal to the unit costs of energy carriers produced in energy subsystem of complex buildings. Therefore, the matrix method of calculating the unit costs of energy carriers is a coordinating procedure in the decomposition model for the preliminary design of the energy management of complex buildings [21].

In the first approximation of the iterative algorithm of decomposition the vectors $\mathbf{k}$ and $\mathbf{k}_F$ of unit costs of the energy carriers is assumed as well as the technical coefficients of feedback character. Having solved the task of optimisation concerning all the branches (Eq.9.25.), and taking into account local restrictions we return to the level of coordination where the corrected balance of energy carriers is set up by means of linear mathematical model [5,15,16], and the corrected vector of unit costs of energy carriers is determined in compliance with the coordinating procedure. The corrected vector of unit costs is then applied to optimise the branches in the successive iteration. The end of the iterative procedure results from the assumed accuracy in the calculation of the unit cost of energy carriers.

9.6. Matrix method for calculating the unit costs of energy carriers

The complexity of energy management due to feedback connections allows the unit costs of the production of energy carriers to be determined merely by means of the method of successive approximation. Thus, for instance, the unit cost of electricity requires knowledge of the unit cost of the driving agent (steam driving the steam turbine or combustion gases driving the gas turbine) which again depends on the a priori unknown unit cost of electricity. An additional difficulty arises from problems connected with the division of costs in cogeneration processes. Therefore the application of the matrix method for determining unit costs in energy management, based on the same principles as the mathematical model of the energy balance, provides a solution of this problem [18]. An indispensable condition of its application is a priori knowledge of the energy balance prepared, based on the mathematical model of the energy management of complex buildings.

The energy carrier consumed in complex buildings may be the main product of basic and peak equipment, a by-product or supply from outside. For this reason, unit costs of the basic and peak part of the main production, by-production of energy carriers and, externally supplied energy carriers are to be distinguished. As far as the consumption of energy carriers is concerned, the average unit cost is to be used, calculated as the weighted average taking into account the cost of transport, changes of the parameters and the cost of distribution of the energy carriers.

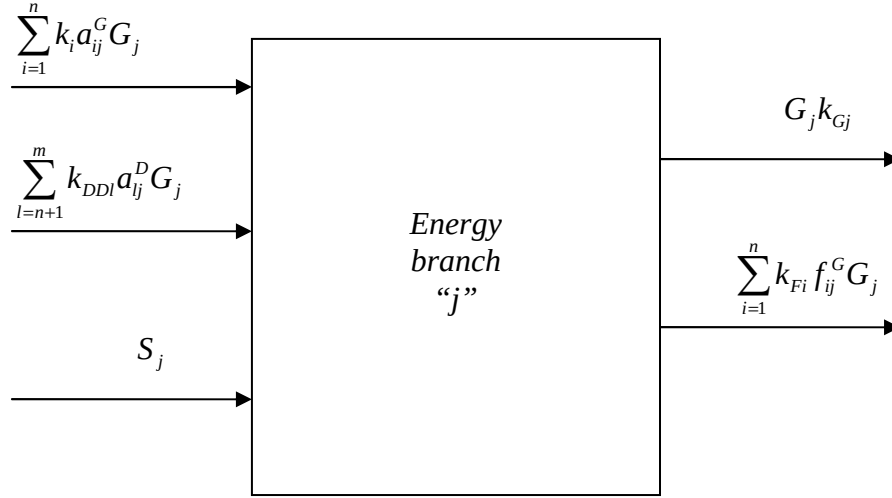


Fig. 9.4. Balance of costs for the energy branch “j” in the case of peak part production

The balance equation of costs concerning the peak part production of the j-th energy branch (Fig. 9.4.) takes the form:

$$\sum_{i=1}^n k_i a_{ij}^G G_j + \sum_{l=n+1}^m k_{DDI} a_{lj}^{GD} G_j + S_j = G_j k_{Gj} + \sum_{i=1}^n k_{Fi} f_{ij}^G G_j \quad (9.33)$$

where:

k_i - weighted average unit cost of the “i-th” energy carrier,

k_{DDI} - unit cost of the “l-th” energy carrier entirely supplied from outside,

k_{Gj} - unit cost of the “j-th” energy carrier produced by peak equipment,

k_{Fi} - unit cost of the “i-th” energy carrier produced as a by-product,

S_j - arbitrary fixed cost.

This equation concerns the case when the j-th energy carrier is produced in the peak equipment accompanied by the by-production of other energy carriers. The term S_j in the balance equation (9.33) comprises all the remaining components of costs beside the cost of the energy carriers. As S_j includes mainly the components of fixed costs, it has been called arbitrary fixed cost.

The average unit cost k_i of the i -th energy carrier is determined by means of the equation:

$$k_i = r_{Pi}k_{Pi} + r_{Gi}k_{Gi} + r_{Fi}k_{Fi} + r_{DGi}k_{DGi} \quad (9.34)$$

where $r_{Pi}, r_{Gi}, r_{Fi}, r_{DGi}$ denote the share of the basic and peak part of main production, by-production and external supplementary supply in the global input of the “ i -th” energy carrier and $k_{Pi}, k_{Gi}, k_{Fi}, k_{DGi}$ denote the unit cost of basic and peak production, by-production and supplementary supplies.

The set of balance equations of the costs of the peak part of the production concerning all the considered energy carriers takes in matrix notation the following form:

$$(\mathbf{A}_G \mathbf{G}^d)^T \mathbf{k} + (\mathbf{A}_{GD} \mathbf{G}^d)^T \mathbf{k}_{DD} + \mathbf{S}_G = \mathbf{G}^d \mathbf{k}_G + (\mathbf{F}_G \mathbf{G}^d)^T \mathbf{k}_F \quad (9.35)$$

where:

$\mathbf{k}$ - vector of weighted average unit costs of energy carriers,

$\mathbf{k}_{DD}$ - vector of the unit costs of energy carriers entirely supplied from outside,

$\mathbf{S}_G$ - vector of arbitrary fixed costs concerning the peak part of the production,

$\mathbf{k}_G$ - vector of the unit costs of peak part of the production,

$\mathbf{k}_F$ - vector of the unit costs of by-production,

“ d ” denotes the construction of a diagonal matrix from the column vector.

Similarly, the balancing of the production costs of the basic part of the production takes the following form:

$$(\mathbf{A}_P \mathbf{P}^d)^T \mathbf{k} + (\mathbf{A}_{PD} \mathbf{P}^d)^T \mathbf{k}_{DD} + \mathbf{S}_P = \mathbf{P}^d \mathbf{k}_P + (\mathbf{F}_P \mathbf{P}^d)^T \mathbf{k}_F \quad (9.36)$$

where:

$\mathbf{k}_P$ - vector of the unit costs of basic part of the production,

$\mathbf{S}_P$ - vector of arbitrary fixed costs concerning the basic part of the production.

The vector of weighted average unit costs of energy carriers is expressed by the equation:

$$\mathbf{k} = \mathbf{r}_P^d \mathbf{k}_P + \mathbf{r}_G^d \mathbf{k}_G + \mathbf{r}_F^d \mathbf{k}_F + \mathbf{r}_{DG}^d \mathbf{k}_{DG} \quad (9.37)$$

where:

$\mathbf{r}_P^d$ - diagonal matrix of the shares of basic part of the main production,

$\mathbf{r}_G^d$ - diagonal matrix of the shares of peak part of the main production,

- $\mathbf{r}_F^d$ - diagonal matrix of the shares of by-production,
 $\mathbf{r}_{DG}^d$ - diagonal matrix of the shares of supplementary supplies of energy carriers,
 $\mathbf{k}_{DG}$ - vector of the unit costs of supplementary supplies.

Equations (9.35), (9.36) and (9.37) constitute the algorithm of the matrix method for calculating the unit costs of energy carriers. The unit costs of by-production are determined using the method of avoided costs [12]. Unit costs of supplementary supplies, as well as unit costs of energy carriers entirely supplied from outside, are input data known a priori.

The presented matrix method permits the unit costs of energy carriers concerning the complex energy management system to be determined with a systems approach. It is pertinent independently of the applied methods of dividing the costs in cogeneration and coupled processes. It is of advantage when the applied auxiliary equations, resulting mainly from the principles of divided costs, do not derange the linearity of the set of equations, only due to the solution of the set of balance equations of the costs.

Example of unit costs calculations

An example is a CHP unit with a back-pressure turbine (Fig.9.5). The back-pressure steam is the basic part of the production of process steam. Electricity is a by-product of the CHP unit produced on the flux of back-pressure steam (process steam) and it is also provided by the national electro-energy system.

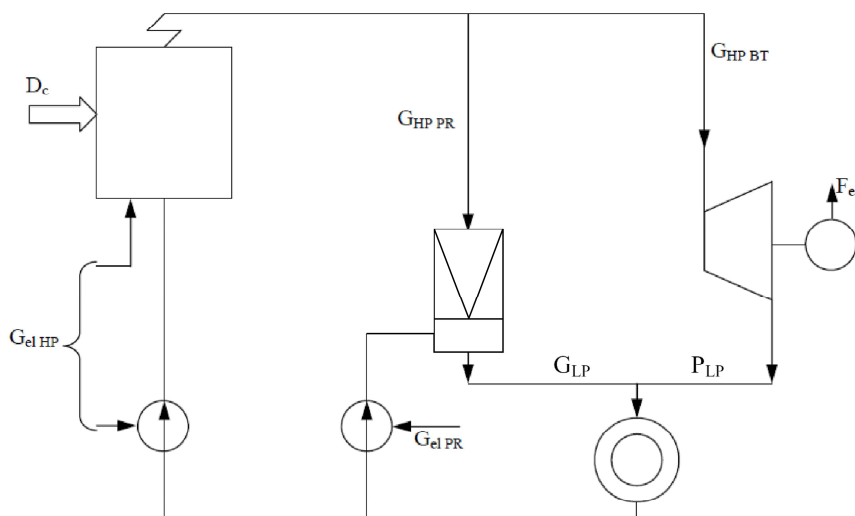


Fig. 9.5. CHP plant with back-pressure turbine

The balance equations of the costs concerning high pressure steam, peak and basic production of low-pressure steam for heating purposes take the forms:

$$D_c k_c + G_{el\ HP} k_{el} + S_{HP} = (G_{HP\ PR} + G_{HP\ BT}) k_{HP} \quad (a)$$

$$G_{HP\ PR} k_{HP} + G_{el\ PR} k_{el} + S_{PR} = G_{LP} k_{GLP} \quad (b)$$

$$G_{HP\ BT} k_{HP} + S_{BT} = P_{LP} k_{PLP} + F_{el} k_{Fel} \quad (c)$$

where:

$G_{HP\ BT}$ - consumption of high-pressure steam in back-pressure turbine,

$G_{HP\ PR}$ - consumption of high-pressure steam by pressure-reducing valve station,

D_c - supply of hard coal,

k_c - unit cost of hard coal,

$G_{el\ HP}$ - consumption of electricity by steam boiler,

$G_{el\ PR}$ - consumption of electricity by pressure-reducing valve station,

G_{LP} - peak part production of low-pressure steam,

P_{LP} - basic part production of low-pressure steam (back-pressure steam),

$k_{G\ LP}$ - unit cost of peak part of the production of low-pressure steam,

$k_{P\ LP}$ - unit cost of basic part of the production of low-pressure steam,

k_{HP} - unit cost of high-pressure steam,

k_{el} - weighted average unit cost of electricity,

k_{Fel} - unit cost of electricity produced as a by-product,

S_{HP}, S_{PR}, S_{BT} , - arbitrary fixed cost of the steam boiler, pressure-reducing valve and back pressure turbine, respectively, excluding the costs of energy carriers,

F_{el} - by-production of electricity.

The weighted average unit cost of electricity results from:

$$k_{el} = \frac{F_{el}}{F_{el} + D_{el}} k_{Fel} + \frac{D_{el}}{F_{el} + D_{el}} k_{Del} \quad (d)$$

where:

D_{el} - external supply of electricity,

k_{Del} - unit cost of electricity supplied from outside.

Based on the principle of avoided costs concerning the cogeneration system we can write:

$$k_{Fel} = k_{Del} \quad (e)$$

Hence:

$$k_{el} = k_{Del} \quad (f)$$

Based on Eq. (a) we can calculate:

$$k_{HP} = \frac{D_c k_c + G_{el HP} k_{Del} + S_{HP}}{G_{HP PR} + G_{HP BT}} \quad (g)$$

and from Eq. (b) and (c) we get:

$$k_{GLP} = \frac{G_{HP PR}}{G_{LP}} \left(\frac{D_c k_c + G_{el HP} k_{Del} + S_{HP}}{G_{HP PR} + G_{HP BT}} \right) + \frac{G_{el PR}}{G_{LP}} k_{Del} + \frac{S_{PR}}{G_{LP}} \quad (h)$$

$$k_{PLP} = \frac{G_{HP BT}}{P_{LP}} \left(\frac{D_c k_c + G_{el HP} k_{Del} + S_{HP}}{G_{HP PR} + G_{HP BT}} \right) + \frac{S_{BT}}{P_{LP}} - \frac{F_{el}}{P_{LP}} k_{Del} \quad (i)$$

The unit costs of external supplies, viz. k_{Del} concerning the supplementary supply of electricity and k_c concerning the supply of coal are assumed to be imposed by the suppliers. Arbitrary fixed costs S_{HP} , S_{PR} and S_{BT} are known. The remaining values in Eqs. (h) and (i) result from the energy and mass balance equations concerning CHP plant (Fig. 9.5).

9.7. Example of calculations concerning the application of a descriptive model of complex buildings

9.7.1. Scenario of the energy management of the analysed complex buildings

As an example of complex buildings a typical office building has been chosen. The seven-floor building provides main office services. The floor area of the offices in the building amounts to 8000 m². The building also includes car park floors, which are neither heated nor cooled. In this building there are two types of rooms, viz., offices with fan-coil units and auxiliary rooms with a traditional central heating system.

The fan-coil system is one of the air-conditioning systems used in the building. Fan-coil units are placed in each office which needs to be heated or cooled. This system uses in-room units containing such components as a fan, heating and cooling coils, filters and controls. This is a four-pipe system utilising two independent coils, one for heating and one for cooling. Cooling and heating valves for controlling the coil capacities are installed with their controls in the rooms. A central plant delivers hot or cold water to the fan units. The mechanical ventilation system operates only during office hours. The main air-conditioning unit for the building delivers a suitable quantity of air to all rooms. Individual temperature conditions are ensured by fan-coil units in the offices and by the central heating system in auxiliary rooms. The installation of hot process water supplies heat to the heater in the air-conditioning unit and to the offices via the fan-coil units.

Car parking is situated on four floors. These floors are only ventilated by a mechanical extract ventilation system. The car park consumes electricity only for lighting, controls and monitoring.

The following energy carriers need to be supplied to the subsystem of consumers:

- cooling medium (water-glycol) 6/12°C,
- hot process water (for the central heating system and for the air-conditioning unit) 85/55 °C,
- hot tap water,
- hot process water 60/45 °C (for fan-coil units),
- air from the air-conditioning unit.

The subsystem of consumers includes:

- office rooms with fan-coil air-conditioning,
- auxiliary rooms with a traditional central heating system,
- standard building equipment, such as an emergency systems, fire sensors, and external lighting,

- car park with a mechanical extract ventilation system.

For the energy management of exemplary complex buildings, it was suggested that a small cogeneration unit is to be applied, equipped with a piston combustion engine, a gas microturbine or a fuel cell. It was decided to consider variants of the energy management which satisfy the condition that one cogeneration technique is assigned to every respective variant. For this purpose the criterion of technical compatibility has been applied. Also, the application of the “trigeneration” technique, using the heat from the cogeneration unit in an absorption chiller fed with hot water, was taken into consideration. The possibility of supplying electricity and heat from outside and the production of the cooling agent in a compression refrigerator, were also considered.

The subsystem of consumers in the analysed complex buildings requires process hot water on two temperature levels, as well as hot tap water. Process water feeds the heating installations and the preheater in the air-conditioning centre. Three cooling agents with a different temperature have been taken into account, respectively for the air-conditioning unit, the cooler and store rooms. The production of the cooling agent in an absorption chiller fed with natural gas is presumed to be possible. Moreover, the installation of the following peak equipment has been taken into consideration: a water-heater boiler fed with natural gas or fuel oil, and a compressor refrigerator driven by electricity.

Table 9.1 contains a general list of energy carriers and, among others, the vector $\mathbf{O}^b$ describing the structure of the demand for energy carriers by the subsystem of consumers. Besides energy carriers consumed by the subsystem of consumers (expressed by the binary vector $\mathbf{O}^b$ the general specification contains energy carriers, the production of which results from interbranch connections in the energy subsystem. The general specification contains ten energy carriers produced as major products and four energy carriers supplied from outside. Non-zero elements of the vector $\mathbf{O}^b$ provide information about the direct consumption of energy carriers in the subsystem of consumers. Zero elements of the vector $\mathbf{O}^b$ concern energy carriers which are potentially consumed only in the energy subsystem. Non-zero elements of the vectors $\mathbf{B}_G^b$ and $\mathbf{B}_D^b$ represent energy carriers produced in the energy subsystem of complex buildings and those which are supplied from outside.

The preliminary design of the energy subsystem of the considered complex building concerns the modernisation of the energy management. Instead of supplying heat and electricity, the CHP unit has been suggested. Based on the general specification of energy carriers (Table 9.1) a list of energy equipment has been drawn up (Table 9.2). This list

comprises technically available and economically feasible energy equipment selected as needed by the subsystem of consumers.

Table 9.1. General list of energy carriers and the structure of the vectors $\mathbf{B}_G^b$ and $\mathbf{B}_D^b$ production and supplies of energy carriers and vector $\mathbf{O}^b$ of the demand for energy carriers for the subsystem of consumers.

i	Energy carrier	$\mathbf{B}_G^b$	$\mathbf{B}_D^b$	$\mathbf{O}^b$
1	Electricity	1	0	1
2	Heat	1	0	0
3	Cold	1	0	0
4	Hot process water for absorption chiller	1	0	0
5	Cooling medium 6/12°C	1	0	1
6	Hot process water I 60/45°C	1	0	1
7	Hot process water II 85/55°C	1	0	1
8	Hot tap water	1	0	1
9	Air from air conditioning unit	1	0	1
10	Ventilation air	1	0	1
11	Drinking water	0	1	1
12	Natural gas	0	1	1
13	Heating oil	0	1	0
14	Diesel oil	0	1	0

Table 9.2. Energy equipment for the considered office building

Symbol	Equipment
U1	Refrigeration unit
U2	Absorption chiller I – powered by hot water
U3	Absorption chiller II – powered by hot natural gas
U4	Water heaters powered by heating oil
U5	Water heaters powered by natural gas
U6	CHP system with piston engine powered by diesel oil
U7	CHP system with microturbine powered by natural gas
U8	CHP system with fuel cell powered by natural gas
U9	Peak water heater powered by natural gas
U10	Peak water heater powered by heating oil
U11	Peak refrigeration unit
U12	Air conditioning unit
U13	Exhaust ventilation system
U14	Heat exchanger –cooling medium 6/12°C
U15	Heat exchanger –hot water 60/45°C
U16	Heat exchanger –hot water 85/55°C
U17	Heat exchanger –hot tap water

9.7.2. Elaboration of the set of admissible variants

On the basis of the scenario of the energy management of the analysed complex buildings and information provided in Table 9.1 and Table 9.2, sets of projects and designs have been formulated (Table 9.3).

Further on, they form the basis for setting up all the realisable variants of the energy management of complex buildings. This set is then verified according to the criterion of compatibility of the technologies and the elimination of unnecessary technical solutions.

The set of the project and designs is presented as a binary matrix $\mathbf{\Pi}$ collated in Table 9.3. This matrix comprises all the projects and designs to be realised in the exemplary building. Ten projects and 27 designs have been distinguished. The rows in the matrix $\mathbf{\Pi}$ correspond to the respective designs, and the columns to the respective energy equipment in the analysed complex buildings. The last column concerns the supply of energy carriers from outside. Thus, for example, project No 1, comprising four designs, concerns the production or supply of electricity. Design No 1 (first row in Table 3) consists in supplying electricity from outside (only supply without own production). The next three designs comprise the successive applications of a CHP unit with a piston engine fed with diesel oil, a CHP unit with a gas microturbine fed with natural gas and a CHP unit with a fuel cell together with a supplementary supply of electricity from the electrical grid.

Each one of the 27 designs is described by a binary matrix of the interconnections $\mathbf{A}_{pP}^b, \mathbf{A}_{pG}^b, \mathbf{F}_{pP}^b, \mathbf{F}_{pG}^b$. Based on the matrix of interconnections concerning the respective design, the binary matrix $\mathbf{Z}^b$ has been elaborated.

Table 9.4 includes the binary matrix $\mathbf{Z}^b$ which shows the structure of the consumption of energy carriers in the set of designs in the analysed building. Design No 2, for instance, comprising the production of electricity in a CHP system with a piston combustion engine (second column in Table 9.3) is connected with a consumption of electricity and diesel oil (row 1 and 14 in the matrix $\mathbf{Z}^b$). In the case of the analysed building the supply of energy carriers is not connected with the consumption of other energy carriers; therefore column 1 in the matrix $\mathbf{Z}^b$ contains only zero elements. Other external supplies (drinking water, natural gas, heating oil and diesel oil) come all from outside and for this reason they are contained only in Table 9.4. As in the case of electricity, columns with zero elements corresponds to those in the matrix $\mathbf{Z}^b$. Table 9.4 does not contain this column.

The set of all possible variants of the energy management system have been formulated by choosing one design from each project. The number of variants which may be realised, determined in such a way, is considerable. For example, in the being considered case the number of all possible variants has been calculated as $N=396$. However, many of those variants are not justified from the viewpoint described in subsection 9.2. In the considered example, after the elimination of unnecessary solutions, a subset of 28 variants of the energy management system has been selected. For each variant of the energy management structure, the binary vector $\mathbf{W}_i^b$ is found. Table 9.5 shows vectors $\mathbf{W}_i^b$ for all the considered variants. Each design is described by means of the binary matrices $\mathbf{A}_{pP}^b, \mathbf{A}_{pG}^b, \mathbf{F}_{pP}^b, \mathbf{F}_{pG}^b$ concerning the structure of the consumption and by-production of energy carriers.

On the basis of the matrices $\mathbf{A}_{pP}^b, \mathbf{A}_{pG}^b, \mathbf{F}_{pP}^b, \mathbf{F}_{pG}^b$ and equations (9.5-9.13) the input-output matrices for all variants have been found. Table 9.6 shows an exemplary matrix $\mathbf{A}_p^b + \mathbf{F}_p^b$ for the variant W4. An energy flow diagram of energy management of complex buildings can be drawn by using the matrix $\mathbf{A}_p^b + \mathbf{F}_p^b$.

Figure 9.6 shows the energy flow diagram of the variant W4 of the energy management structure. Variant W4 represents the application of a CHP unit powered with diesel oil in the analysed office building. The CHP unit produces hot water for the absorption chiller besides heat and electricity. During the peak period heat is also produced in the peak water-heater fuelled with natural gas. The peak cold is delivered from the refrigeration chiller powered by electricity. The next step in the procedure is the investigation of the whole energy equipment in the energy management of complex buildings and the replacement of the binary elements of the matrix $\mathbf{A}_p^b + \mathbf{F}_p^b$ with concrete coefficients of energy consumption. After replacing the binary elements, the mathematical model of the energy balance of complex buildings is applied [15]. Using this model, it is possible to calculate the consumption of all energy carriers concerning all the variants of the energy management structure.

Table 9.3. Matrix of the projects and subsets of design II

Project	No. of design	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	SUPPLY
1 Electricity	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
2 Heat	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	6	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	8	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	9	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
	13	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
	15	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
	16	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
3 Cold	17	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	18	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	19	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4 Hot process water for absorption chiller I	20	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	21	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	22	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
5 Cooling medium I 6/12°C	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
6 Hot process water I 60/45°C	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
7 Hot process water II 85/55°C	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8 Hot tap water	26	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9 Air from air conditioning unit	27	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
10 Ventilation air		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Table 9.4. Binary matrix Z^b -consumption of energy carriers in set of designs

Energy carrier/Design	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1 Electricity	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2 Heat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0
3 Cold	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
4 Hot process water for abs. chiller I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5 Cooling medium I 6/12°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6 Hot process water I 60/45°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7 Hot process water II 85/55°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8 Hot tap water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9 Air from air conditioning unit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10 Ventilation air	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 Drinking water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
12 Natural gas	0	0	1	1	0	1	1	0	1	1	0	1	1	1	1	0	0	1	0	1	1	0	0	0	0	0	0
13 Heating oil	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
14 Diesel oil	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

Table 9.5. Set of all considered variants of the energy management structure

	Project	No. of design	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25	W26	W27	W28	
1	Electricity	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
		2	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
		5	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Heat	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
		7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
		8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		10	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		11	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		12	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
		15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
3	Cold	16	1	0	1	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	0	0	0	0	0
		17	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
4	Hot process water for absorption chiller I	18	0	1	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0
		19	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Cooling medium I 6/12°C	20	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
		22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	Hot tap water	25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		26	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	Air from air conditioning unit	27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		28	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Drinking water	29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		30	0	0	0	0	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	0	0
13	Heating oil	31	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		32	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9.6. Binary Input-output matrix $\mathbf{A}_p^b + \mathbf{F}_p^b$ - variant W4

	Energy carrier/Project	1	2	3	4	5	6	7	8	9	10
1	Electricity	1	1	1	1	1	1	1	1	1	0
2	Heat	0	0	0	1	0	1	1	1	0	0
3	Cold	0	0	0	0	1	0	0	0	0	0
4	Hot process water for abs. chiller I	0	0	1	0	0	0	0	0	0	0
5	Cooling medium I 6/12°C	0	0	0	0	0	0	0	0	1	0
6	Hot process water I 60/45°C	0	0	0	0	0	0	0	0	0	0
7	Hot process water II 85/55°C	0	0	0	0	0	0	0	0	1	0
8	Hot tap water	0	0	0	0	0	0	0	0	0	0
9	Air from air conditioning unit	0	0	0	0	0	0	0	0	0	0
10	Ventilation air	0	0	0	0	0	0	0	0	0	0
11	Drinking water	0	0	0	0	0	0	0	1	0	0
12	Natural gas	0	1	0	0	0	0	0	0	0	0
13	Heating oil	0	0	0	0	0	0	0	0	0	0
14	Diesel oil	1	1	0	0	0	0	0	0	0	0

9.7.3. Energy balance for the selected variant of energy management of complex buildings

In a detailed energy analysis the variant W4 has been chosen (Fig. 9.6.). In the analysis of variant W4 the following data have been taken into account:

energy efficiency of peak gas boiler - $\eta_{Eb} = 85\%$,

CHP coefficient of the cogeneration unit (based on piston engine) - $\sigma = 0.6$,

coefficient of the own needs (electricity) of the cogeneration unit - $\varepsilon = 0.02$,

energy efficiency of the cogeneration unit - $\eta_{E\text{ CHP}} = 87.1\%$,

coefficient of performance of the absorption chiller - $COP_{abs} = 0.7$,

coefficient of performance of the peak compression refrigerator - $COP_p = 3$,

energy efficiency of the system power plant fired with hard coal - $\eta_{E\text{ el}} = 33.9\%$.

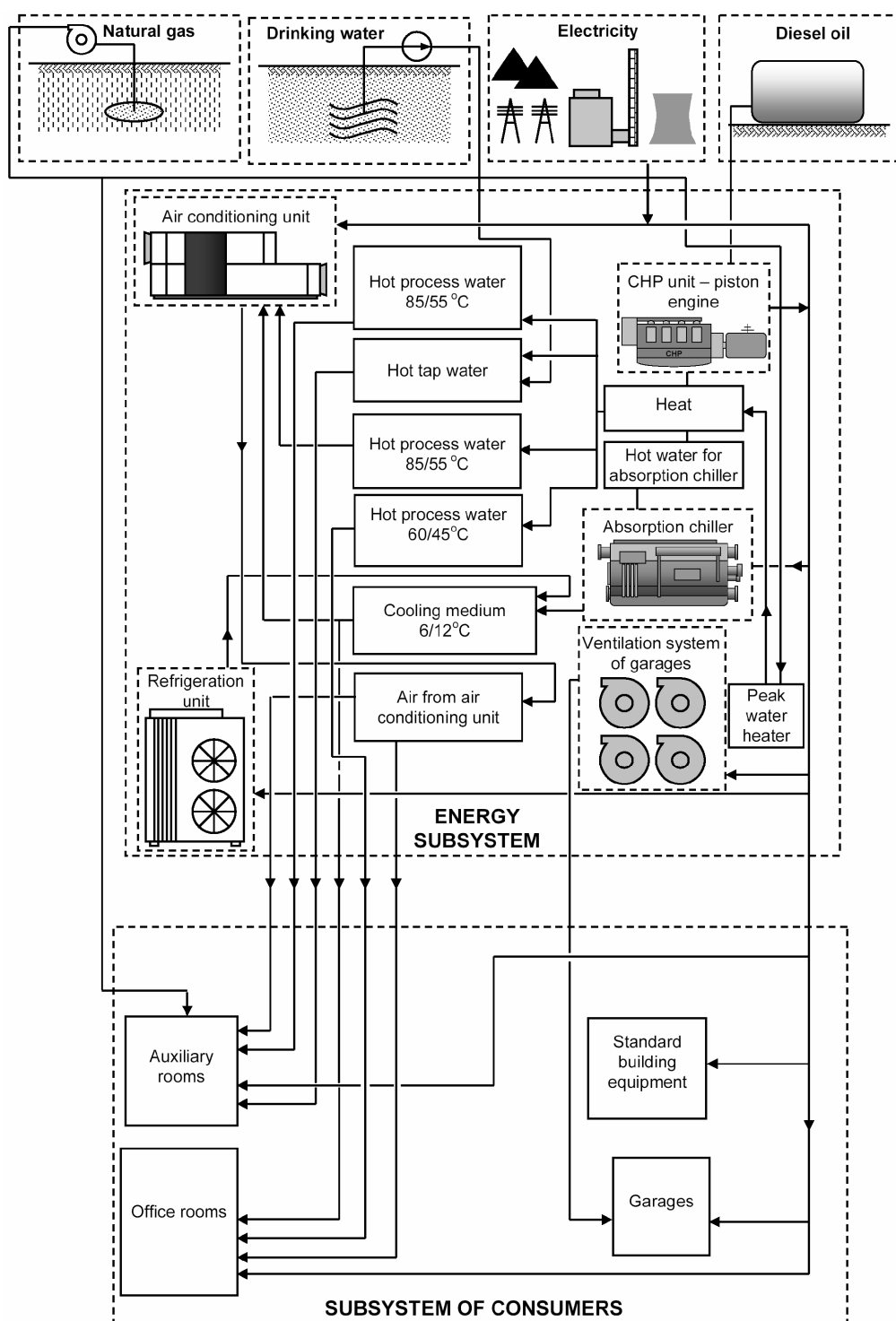


Fig. 9.6 Flow diagram of the energy management structure – variant W4

Based on data concerning the project of the analysed office building and characteristics of energy equipment, the annual consumption of the internal energy carriers for the variant W4 has been calculated. The results of the calculations have been presented below.

The annual electricity consumption in the particular energy branches is (according to Table 9.4):

$$Z_{11} = 54.91 GJ ,$$

$$Z_{12} = 22.05 GJ ,$$

$$Z_{13} = 75.25 GJ ,$$

$$Z_{14} = 11.03 GJ ,$$

$$Z_{15} = 140.3 GJ ,$$

$$Z_{16} = 7.88 GJ ,$$

$$Z_{17} = 44.1 GJ ,$$

$$Z_{18} = 3.62 GJ ,$$

$$Z_{19} = 269.9 GJ .$$

The annual consumption of heat for the production of hot process water for the absorption chiller is:

$$Z_{24} = 1290.697 GJ .$$

The annual consumption of heat for the production of hot process water 60/45°C is:

$$Z_{26} = 1677.11 GJ .$$

The annual consumption of heat for the production of hot process water 85/55°C is:

$$Z_{27} = 1827.66 GJ .$$

The annual consumption of heat for the production of hot tap water is:

$$Z_{28} = 170.53 GJ .$$

The overall annual heat demand is:

$$Q = Z_{24} + Z_{26} + Z_{27} + Z_{28} = 4965.33 GJ .$$

The annual heat production by the CHP unit is:

$$Q_{CHP} = 3972.26 GJ .$$

The annual heat production by the peak gas boiler is:

$$Q_p = 993.07 GJ .$$

The annual consumption of cold for the production of the cooling medium (water-glycol 6/12°C) is:

$$Z_{35} = 1129.36 GJ .$$

The annual production of the cooling medium by the peak compression refrigerator is:

$$Q_{Cp} = 22587 GJ .$$

The annual production of the cooling medium by the absorption chiller is:

$$Q_{C\ abs} = 903.49\ GJ .$$

The annual heat consumption by the absorption chiller is:

$$Z_{4\ 3} = 1290.697\ GJ .$$

The annual consumption of the cooling agent by the air-conditioning unit is:

$$Z_{5\ 9} = 69.78\ GJ .$$

The annual heat consumption by the air-conditioning unit is:

$$Z_{7\ 9} = 975.9\ GJ .$$

The annual consumption of drinking water for the production of hot tap water is:

$$Z_{11\ 8} = 994.6\ Mg .$$

The annual consumption of the chemical energy of natural gas for the production of heat (in peak boilers) is:

$$Z_{12\ 2} = \frac{Q_p}{\eta_{Ek}} = 1168.47\ GJ \quad (9.38)$$

In the considered variant W4 electricity is a by-product of the CHP unit. It has been assumed that heat is the main product (as in system CHP units). Heat produced by the CHP unit is consumed entirely by the analysed complex building. The peak demand for heat is covered by the gas boiler. The annual by-production of electricity U_{12} is calculated from relation:

$$U_{12} = Q_{CHP} \cdot \sigma = 2383.36\ GJ$$

The consumption of the chemical energy of diesel oil for the production of electricity by the CHP unit is calculated based on the principle of avoided expenditure of fuel (similar to the principle of avoided costs). According to this principle the production of electricity in the CHP unit should be charged with the consumption of the chemical energy of fuel as in the substituted system power plant:

$$Z_{14\ 1} = \frac{U_{12}}{\eta_{El}} = 7030.56\ GJ \quad (9.39)$$

The annual consumption of the chemical energy of diesel oil for heat production is:

$$Z_{14\ 2} = \frac{Q_{CHP} + U_{12}}{\eta_{E\ CHP}} - \frac{U_{12}}{\eta_{El}} = 266.37\ GJ \quad (9.40)$$

PES (Primary Energy Savings) for this CHP unit is described by the relation:

$$PES = 1 - \frac{\frac{1+\sigma}{\eta_{E\,CHP}}}{\frac{1}{\eta_{ref\,h}} + \frac{\sigma}{\eta_{ref\,el}}} = 0.297 \quad (9.41)$$

where:

$\eta_{ref\,h} = 0,9$ – reference efficiency of heat production,

$\eta_{ref\,el} = 0,4$ – reference efficiency of electricity production.

PES calculated for the cogeneration unit under consideration represent a rather high value. Such a high value results from the high value of the considered energy efficiency of the cogeneration unit and its coefficient of cogeneration. Figure 9.7 shows values of PES versus these coefficients (σ and $\eta_{E\,CHP}$).

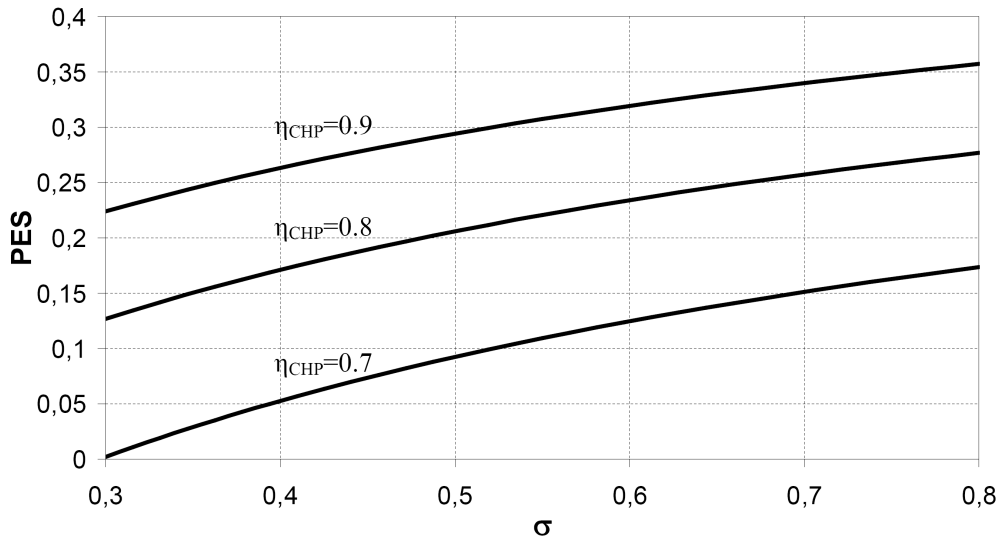


Fig. 9.7 PES versus to σ and $\eta_{E\,CHP}$

Table 9.7 presents the results of a systems analysis for the variant W4 of energy management of the analysed office building. It includes the annual consumption of all energy carriers considered in the building. Figure 9.8 presents a comparison of two variants (W1 and W4) with respect to the annual consumption of energy carriers which are supplied to the office building. W1 is characterised by supplying heat and electricity to the building from outside.

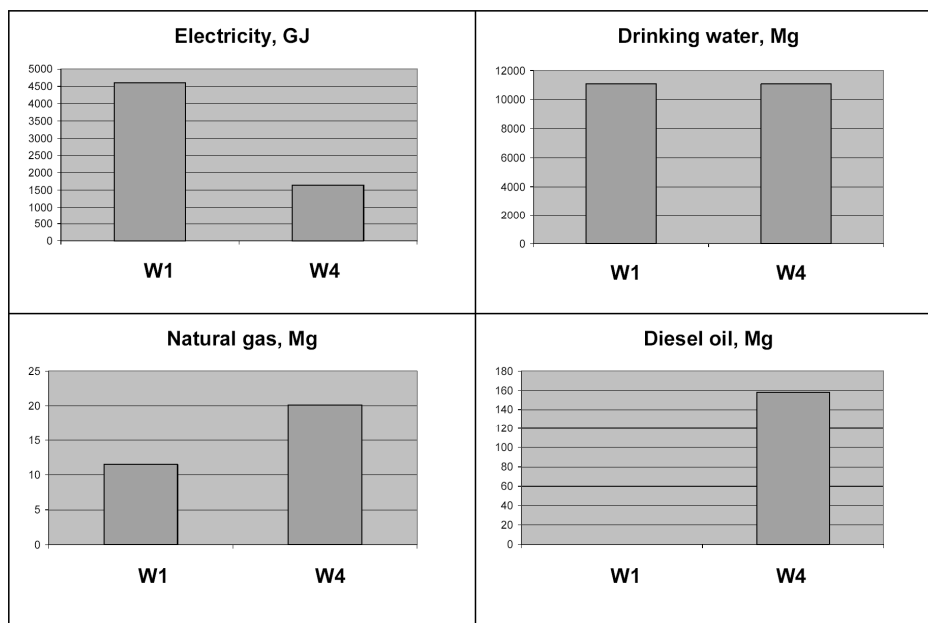


Fig. 9.8 Annual consumption of energy carriers which are supplied to the analysed office building – variant W1 and variant W4 of energy management structure

Table 9.7. Results of sample in the calculations in the input-output table of considered office building - variant W4

NO.	ENERGY CARRIER	UNIT	PRODUCTION	SUPPLY	INTERBRANCH FLOWS OF ENERGY CARRIERS														
					ENERGY SUBSYSTEM										SUBSYSTEM OF CONSUMERS				
					1	2	3	4	5	6	7	8	9	10	Office rooms	Auxiliary rooms	Garages	Standard equipment of the building	
1	Electricity	GJ	2383.36	1608.15	54.91	22.05	75.25	11.03	140.3	7.88	44.1	3.62	269.9	0	2639.22	79.22	397.33	246.7	
2	Heat	GJ	4966.00	0	0	0	0	1290.7	0	1677.11	1827.66	170.53	0	0	0	0	0	0	
3	Cold	GJ	1129.36	0	0	0	0	0	1129.36	0	0	0	0	0	0	0	0	0	
4	Hot process water for abs. chiller	GJ	1290.70	0	0	0	1290.697	0	0	0	0	0	0	0	0	0	0	0	
5	Cooling medium I 6/12°C	GJ	1129.36	0	0	0	0	0	0	0	0	0	69.78	0	1059.58	0	0	0	
6	Hot process water I 60/45°C	GJ	1677.11	0	0	0	0	0	0	0	0	0	0	0	1677.11	0	0	0	
7	Hot process water II 85/55°C	GJ	1827.70	0	0	0	0	0	0	0	0	0	975.9	0	0	851.8	0	0	
8	Hot tap water	Mg	994.60	0	0	0	0	0	0	0	0	0	0	0	0	994.6	0	0	
9	Air from air conditioning unit	Mg	75908.00	0	0	0	0	0	0	0	0	0	0	0	45544.8	30363.2	0	0	
10	Ventilation air	Mg	435591.00	0	0	0	0	0	0	0	0	0	0	0	0	0	435591	0	
11	Drinking water	Mg	0	11079.6	0	0	0	0	0	0	0	994.6	0	0	0	10085	0	0	
12	Natural gas	GJ	0	1744.313	0	1168.313	0	0	0	0	0	0	0	0	0	576	0	0	
13	Heating oil	GJ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
14	Diesel oil	GJ	0	7296.926	7030.56	266.37	0	0	0	0	0	0	0	0	0	0	0	0	

Due to the installation of the CHP the supply of electricity from outside has been reduced threefold, whereas the supply of natural gas has been increased twofold. For the variant with CHP the supply of diesel oil is indispensable.

The analysis has been performed based on the mathematical model of the energy balance of complex buildings [15]. The results of this analysis may be useful in further investigations in order to find the optimal variant of energy management of complex buildings.

The uncertainty of the input data influences the reliability of the obtained results of calculation in a various degree. In order to assess this influence a sensitivity analysis has been applied. The data which exert the largest influence on the energy consumption in the variant

W4 of the analysed building have been chosen to analyse the sensitivity. The uncertainty of the following coefficients has been considered: σ - CHP coefficient, $\eta_{E\text{ CHP}}$ - efficiency of the CHP unit, and COP_{abs} - coefficient of performance of the absorption chiller. Figures 9.9 to 9.11 show exemplary results of the sensitivity analysis.

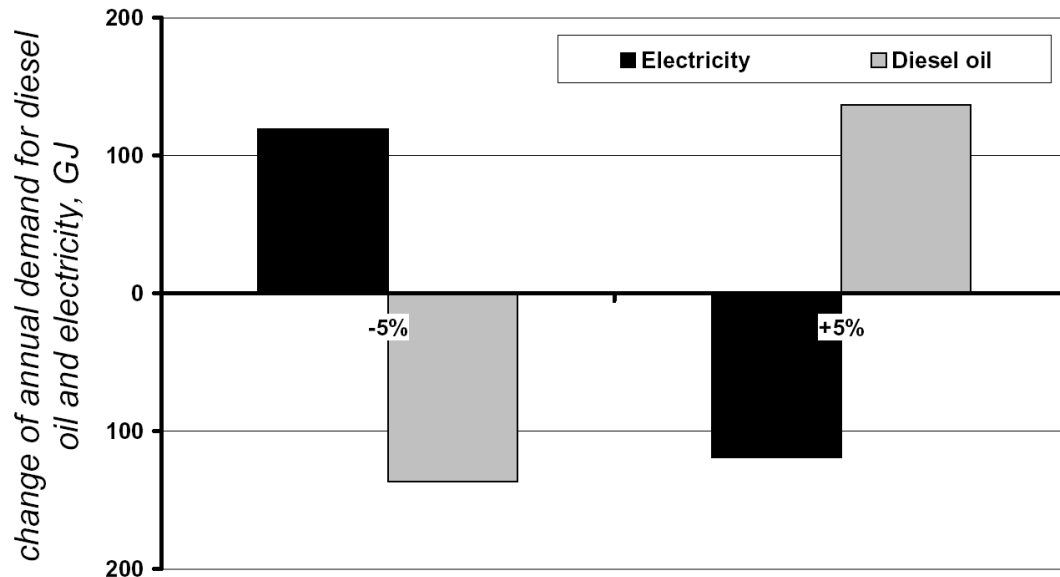


Fig. 9.9 Change of annual demand for diesel oil and electricity supplied to the building caused by variation of CHP coefficient σ

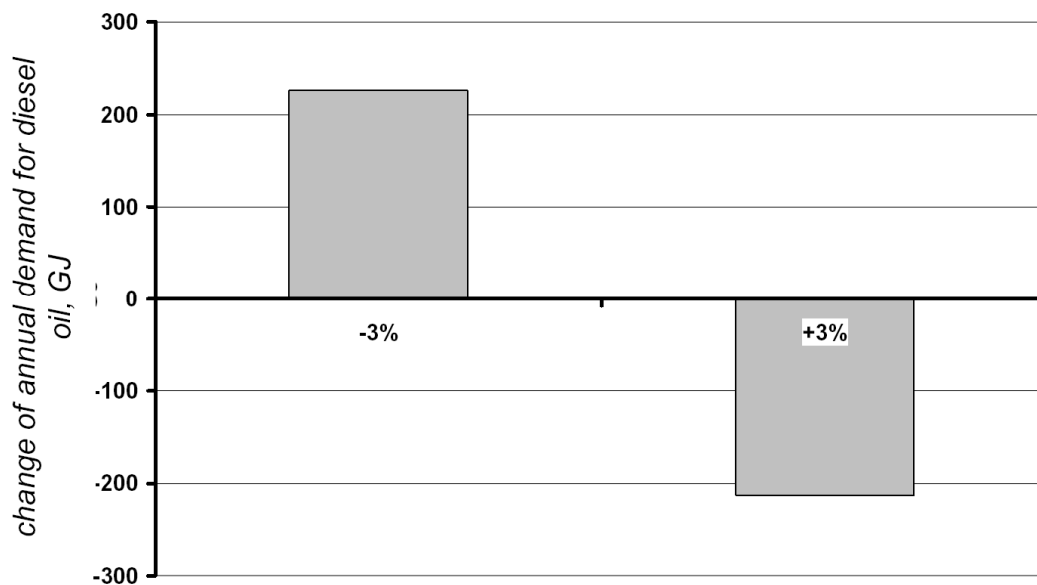


Fig. 9.10 Change of annual demand for diesel oil (in GJ) supplied to the building with respect to the energy efficiency of the CHP unit $\eta_{E\text{ CHP}}$

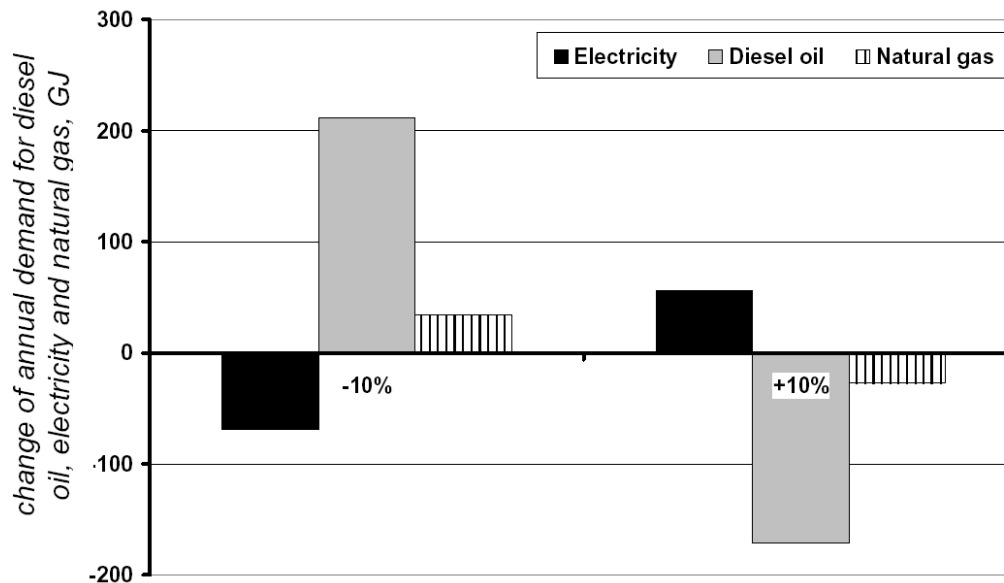


Fig. 9.11 Change of annual demand for electricity, diesel oil and natural gas supplied to the building caused by variation of coefficient of performance of absorption chiller COP_{abs}

The increase of the cogeneration coefficient (a higher production of electricity with the same demand for heat) involves a reduction in the supply of electricity from outside. Although the fuel input in CHP increases simultaneously, the energy savings of fuel also increase in comparison with separate production of heat and electricity. The increase of CHP efficiency, which amounts to 3 per cent effects a reduction of about 212 GJ of diesel oil per year. The increased coefficient of performance (COP) of the absorption chiller by 10 per cent effects a drop in diesel oil consumption of about 171 GJ per year and the consumption of natural gas of about 27 GJ per year. Simultaneously, however, the supply of electricity increases due to the decreased production in cogeneration.

9.8. Example of the application of an optimisation model for the choice of an energy-management structure for industrial-urban complex

9.8.1. Scenario of the energy management of the industrial-urban complex

The subject of the preliminary design is the choice of the optimal structure of the energy subsystem producing energy carriers both for the needs of industrial and municipal consumers [22]. Such industrial-urban complexes are often encountered in industrial regions. The

industrial subsystem is not only the consumer of energy carriers but also the producer of some of them (e.g., by-production of low-calorific gas or waste heat).

It has been decided that the energy management for the industrial-urban complex under consideration is to be based on a CHP plant. The installation of a back-pressure turbo-generator or extraction-condensing turbo-generator may be applied. The boiler-house of the CHP will be equipped with double-fuel boilers. These may be either gas-and-coal or gas-and-oil boilers. The fundamental fuel in the boilers will be low-calorific technological fuel gas provided by the subsystem of industrial consumers. Low-pressure steam will be used for space heating and ventilation, as well as for the production of hot tap water (mainly for the subsystem of municipal consumers) and also for technological purposes in the subsystem of industrial consumers. For the production of process air it is planned to install either blowers driven by steam turbines (turbo-blowers) or blowers driven by electric motors. The choice of equipment for the water-softening plant has not been analysed, because its capacity is determined by the nominal capacity of the steam boilers.

The subsystem of consumers in this industrial-urban complex comprises industrial processes and municipal branches (e.g., a district heating system and a municipal water system). Table 9.8 contains the binary vector $\mathbf{O}^b$ describing the structure of the demand for energy carriers by the subsystem of consumers. Non-zero elements provide information about energy carriers directly consumed in the subsystem of consumers. Zero elements concern energy carriers which are consumed only in the energy subsystem. The set of energy equipment and engines for the production of the considered energy carriers is also shown in Table 9.8.

Table 9.8. General specification of energy carriers, structure vector $\mathbf{O}^b$ of the demand for energy carriers for the technological subsystem and set of energy equipment and engines

Energy carrier	$\mathbf{O}^b$	Equipment or engines	Symbol
Medium-pressure steam	0	Steam boilers fired with blast-furnace gas and coal	U_1
		Steam boilers fired with blast-furnace gas and oil	U_2
Low-pressure steam 1	1	Extraction-condensing turbine (steam extraction nozzle 0.8 MPa)	U_3
Electrical energy	1	Back-pressure turbine (exhaust pressure 0.8 MPa)	U_4
		Pressure-reducing valve 3.7/0.8 MPa	U_5
Low-pressure steam 2	0	Pressure-reducing valve 0.8/0.12 MPa	U_6
Process air	1	Process air turbo-blowers	U_7
		Electrically driven process air blowers	U_8

Heat	1	Heat exchangers	U_9
Soft water	0	Water-softening plant	U_{10}
Feed water	0	Deaerating heater and pumping station of feed water	U_{11}
Industrial and drinking water	1	Pumping station of industrial and drinking water	U_{12}
Compressed air	1	Air compressors	U_{13}
Power coal	0		
Fuel oil	0		
Natural gas	1		
Low-calorific gas	1		

Ten kinds of energy carriers obtained as main products have been distinguished, one energy carrier (low-calorific technological fuel gas) being a by-product which does not supplement the main production, as well as three energy carriers supplied entirely from outside.

Based on a general specification of energy carriers and specification of engines and energy equipment, presented in Table 9.8, a set of projects and designs has been established with nine projects and 12 designs distinguished (Table 9.9). The symbol $U_4 \wedge U_5 \wedge D_4$, for instance, denotes the back-pressure steam turbine and pressure-reducing valve, as well as the external supply of electrical energy (D_4).

Table 9.9. Projects and designs

t	Project	p	Design
1	Medium-pressure steam	1	U_1
		2	U_2
2	Low-pressure steam 1 Electrical energy	3	$U_3 \wedge U_5 \wedge D_4$
		4	$U_4 \wedge U_5 \wedge D_4$
3	Low-pressure steam 2	5	U_6
4	Process air	6	U_7
		7	U_8
5	Heat	8	U_9
6	Soft water	9	U_{10}
7	Boiler water	10	U_{11}
8	Industrial and drinking water	11	U_{12}
9	Compressed air	12	U_{13}

9.8.2. Elaboration of the set of variants concerning the energy management system and determination of the structure of the binary input-output matrix [20]

According to this scenario (Tables 9.8 and 9.9) the set of all possible variants of the industrial-municipal energy system has been formulated, choosing one design from each project. In the example being considered eight variants of the energy system have been formed (Table 9.10). Figure 9.12 presents a schematic diagram of the energy subsystem of this industrial-urban complex for one of the eight variants, viz., $\{U_1, U_4 \wedge U_5 \wedge D_4, U_6, U_7, U_9, U_{10}, U_{11}, U_{12}, U_{13}\}$ -variant III.

Table 9.10. Variants of energy subsystems

Variant 1	P r o j e c t - t								
	1	2	3	4	5	6	7	8	9
I	U_1	$U_3 \wedge U_5 \wedge D_4$	U_6	U_7	U_9	U_{10}	U_{11}	U_{12}	U_{13}
II	U_1	$U_3 \wedge U_5 \wedge D_4$	U_6	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}
III	U_1	$U_4 \wedge U_5 \wedge D_4$	U_6	U_7	U_9	U_{10}	U_{11}	U_{12}	U_{13}
IV	U_1	$U_4 \wedge U_5 \wedge D_4$	U_6	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}
V	U_2	$U_3 \wedge U_5 \wedge D_4$	U_6	U_7	U_9	U_{10}	U_{11}	U_{12}	U_{13}
VI	U_2	$U_3 \wedge U_5 \wedge D_4$	U_6	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}
VII	U_2	$U_4 \wedge U_5 \wedge D_4$	U_6	U_7	U_9	U_{10}	U_{11}	U_{12}	U_{13}
VIII	U_2	$U_4 \wedge U_5 \wedge D_4$	U_6	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}

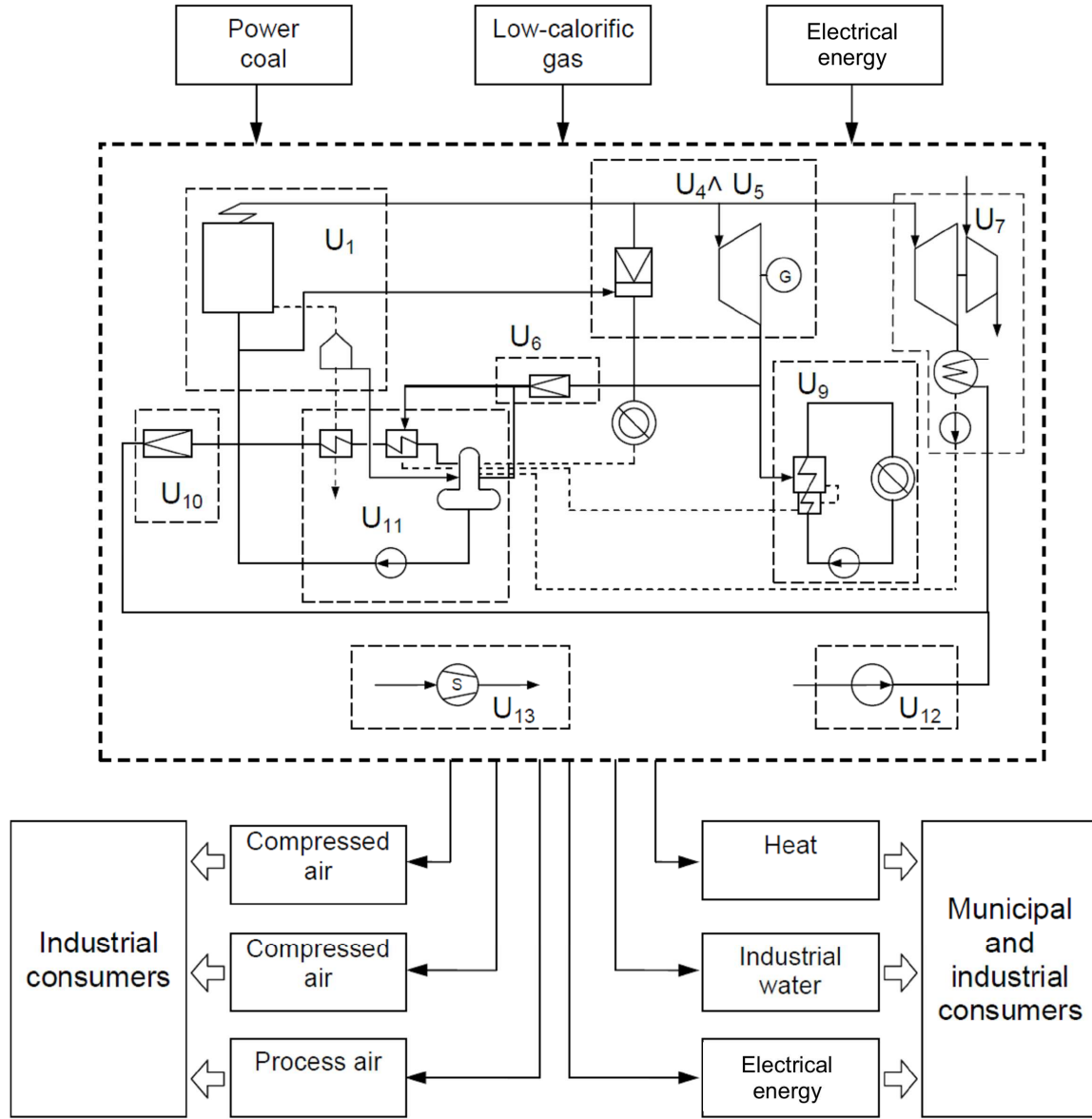


Fig. 9.12. Schematic diagram of energy management of the industrial-urban complex

Each design is described by means of the binary matrices $\mathbf{A}_{pP}^b$, $\mathbf{A}_{pG}^b$, $\mathbf{F}_{pP}^b$, $\mathbf{F}_{pG}^b$ concerning the structure of the consumption and by-production of energy carriers. For example, matrix $\mathbf{A}_G^b$ for variant III is determined as follows:

$$\mathbf{A}_G^b = \mathbf{A}_{1G}^b + \mathbf{A}_{4G}^b + \mathbf{A}_{5G}^b + \mathbf{A}_{6G}^b + \mathbf{A}_{8G}^b + \mathbf{A}_{9G}^b + \mathbf{A}_{10G}^b + \mathbf{A}_{11G}^b + \mathbf{A}_{12G}^b \quad (9.42)$$

Matrix $\mathbf{A}_{1G}^b$ (design U_1 - steam boilers fired with low-calorific technological gas and coal) has a non-zero first column relating to the first column of the matrix $\mathbf{A}_G^b$. Matrix $\mathbf{A}_{4G}^b$ (design $U_4 \wedge U_5 \wedge D_4$ - back-pressure steam turbine and pressure-reducing valve 3.7/0.8 MPa) has a

non-zero second column relating to the second column of the matrix $\mathbf{A}_G^b$. The non-zero elements of this column concern the consumption of medium-pressure steam and boiler water in the pressure-reducing valve 3.7/0.8 MPa. The coefficients concerning the back-pressure steam turbine are presented in the matrix $\mathbf{A}_{4p}^b$. Matrix $\mathbf{A}_{5G}^b$ (design U_6 - pressure-reducing valve 0.8/0.12 MPa) has a non-zero third column (the third column of matrix $\mathbf{A}_G^b$). Matrix $\mathbf{A}_{6G}^b$ (design U_7 - air-process turbo-blowers) has a non-zero fifth column relating to the fifth column of the matrix $\mathbf{A}_G^b$. Matrix $\mathbf{A}_{8G}^b$ (design U_9 - heat exchangers) has a non-zero sixth column concerning the sixth column of the matrix $\mathbf{A}_G^b$. Matrix $\mathbf{A}_{9G}^b$ (design U_{10} - water softening plant) has a non-zero seventh column (the seventh column of the matrix $\mathbf{A}_G^b$). The matrices $\mathbf{A}_{10G}^b, \mathbf{A}_{11G}^b, \mathbf{A}_{12G}^b$ (the designs U_{11} - deaerating heater and pumping station for boiler water, U_{12} - pumping station for industrial water, U_{13} - air compressor) have non-zero columns numbered 8, 9 and 10, respectively. These non-zero columns relate to columns 8,9 and 10 in the matrix $\mathbf{A}_G^b$. The other columns of matrix $\mathbf{A}_G^b$ (4, 11, 12 and 13) are zero-columns. Table 9.11 presents the matrix $\mathbf{A}_G^b$ for variant III.

Table 9.11. "Input-output" binary matrix $\mathbf{A}_G$ (variant III)

Energy carrier	i \ j	1	2	3	4	5	6	7	8	9	10	11	12	13
Medium-pressure steam	1	0	1	0	0	1	0	0	0	0	0	0	0	0
Low-pressure steam 1	2	0	0	1	0	1	1	0	0	0	0	0	0	0
Low-pressure steam 2	3	0	0	0	0	0	0	0	1	0	0	0	0	0
Electrical energy	4	1	0	0	0	1	1	1	1	1	1	0	0	0
Process air	5	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Soft water	7	0	0	0	0	0	0	0	1	0	0	0	0	0
Boiler water	8	1	1	0	0	0	0	0	0	0	0	0	0	0
Industrial water	9	0	0	0	0	1	0	1	0	0	1	0	0	0
Compressed air	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Power coal	11	1	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Low-calorific gas	13	1	0	0	0	0	0	0	0	0	0	0	0	0

The matrices $\mathbf{A}_p^b, \mathbf{F}_p^b$ and $\mathbf{F}_p^b$ for variant III are identical in size to matrix $\mathbf{A}_G^b$. Matrix $\mathbf{A}_p^b$ has only two non-zero elements: a_{12}^p and a_{92}^p , concerning the consumption of medium pressure steam and industrial water by the back-pressure steam turbine. Matrix $\mathbf{F}_p^b$ has non-zero element - f_{42}^p concerning the by-production of electrical energy in the CHP plant. Matrix $\mathbf{F}_G^b$ has three non-zero elements $f_{31}^G, f_{75}^G, f_{76}^G$ related to the by-production of low-pressure steam 2 (expander after the blow-down of the boiler), the by-production of soft water (condensate) in the turbo-blowers and heat exchangers, respectively.

9.8.3. Structural analysis of the binary input-output matrix

Table 9.12 presents the binary input-output matrix ($\mathbf{A}^b + \mathbf{F}^b$) obtained by means of summing up the matrices $\mathbf{A}_p^b, \mathbf{A}_G^b, \mathbf{F}_p^b, \mathbf{F}_G^b$ making use of the principles of Boolean algebra. In this matrix, formed in the order of a universal specification, there are 12 non-zero elements below the main diagonal, which render it difficult to solve the set of balance equations.

Table 9.12 Input-output matrix ($\mathbf{A}^b + \mathbf{F}^b$) variant III

Energy carrier	i \ j	1	2	3	4	5	6	7	8	9	10	11	12	13
Medium-pressure steam	1	0	1	0	0	1	0	0	0	0	0	0	0	0
Low-pressure steam 1	2	0	0	1	0	1	1	0	0	0	0	0	0	0
Low-pressure steam 2	3	1	0	0	0	0	0	0	1	0	0	0	0	0
Electrical energy	4	1	1	0	0	1	1	1	1	1	1	0	0	0
Process air	5	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Soft water	7	0	0	0	0	1	1	0	1	0	0	0	0	0
Boiler water	8	1	1	0	0	0	0	0	0	0	0	0	0	0
Industrial water	9	0	1	0	0	1	0	1	0	0	1	0	0	0
Compressed air	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Power coal	11	1	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Low-calorific gas	13	1	0	0	0	0	0	0	0	0	0	0	0	0

Next the matrix $(\mathbf{A}^b + \mathbf{F}^b)$ is transformed by means of the algorithm of structural analysis. First of all the energy branches are divided into three groups: “input”- type, “centre”- type and “output”-type. The division of the matrix $(\mathbf{A}^b + \mathbf{F}^b)$ into three groups is shown in Table 9.13. In the input-output binary matrix $(\mathbf{A}^b + \mathbf{F}^b)$ divided into blocks, the number of non-zero elements below the main diagonal has been reduced to only five.

Table 9.13 Input-output binary matrix $(\mathbf{A}^b + \mathbf{F}^b)$ divided into blocks

Energy carrier	i \ j	1	2	3	4	5	6	7	8	9	10	11	12	13
Electrical energy	1	0	0	0	1	1	0	1	1	1	1	1	1	0
Power coal	2	0	0	0	1	0	0	0	0	0	0	0	0	0
Low-calorific gas	3	0	0	0	1	0	0	0	0	0	0	0	0	0
Medium-pressure steam	4	0	0	0	0	1	0	0	0	0	1	0	0	0
Low-pressure steam 1	5	0	0	0	0	0	1	0	0	0	1	1	0	0
Low-pressure steam 2	6	0	0	0	1	0	0	0	1	0	0	0	0	0
Soft water	7	0	0	0	0	0	0	0	1	0	1	1	0	0
Boiler water	8	0	0	0	1	1	0	0	0	0	0	0	0	0
Industrial water	9	0	0	0	0	1	0	1	0	0	1	0	1	0
Process air	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat	11	0	0	0	0	0	0	0	0	0	0	0	0	0
Compressed air	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas	13	0	0	0	0	0	0	0	0	0	0	0	0	0

In the next step, strongly coherent subsystems are determined among the energy branches belonging to the centre group. The centre matrix $(\mathbf{A}^b + \mathbf{F}^b)_c$ is then transformed. For this purpose the matrix $\mathbf{C}$ is calculated from equation (9.14). In table 9.14 the successive powers of the matrix $(\mathbf{A}^b + \mathbf{F}^b)_c$ have been gathered.

Table 9.14. Set of the successive powers of the matrix $(\mathbf{A}^b + \mathbf{F}^b)_c$

$(\mathbf{A}^b + \mathbf{F}^b)_c$	$(\mathbf{A}^b + \mathbf{F}^b)_c^2$

$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}$
$(\mathbf{A}^b + \mathbf{F}^b)_c^3$	$(\mathbf{A}^b + \mathbf{F}^b)_c^4$
$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}$

The successive matrices $\mathbf{C}$ according to Eqs. (9.14) and (9.15) are as follows:

$$\mathbf{C}_1 = \sum_{s=1}^1 (\mathbf{A}^b + \mathbf{F}^b)_c^s = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\mathbf{C}_2 = \sum_{s=1}^2 (\mathbf{A}^b + \mathbf{F}^b)_c^s = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$\mathbf{C}_3 = \sum_{s=1}^3 (\mathbf{A}^b + \mathbf{F}^b)_c^s = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$\mathbf{C}_4 = \sum_{s=1}^4 (\mathbf{A}^b + \mathbf{F}^b)_c^s = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

Because:

$$\mathbf{C}_3 = \mathbf{C}_4$$

we can write:

$$\mathbf{C} = \mathbf{C}_3 = \mathbf{C}_4$$

The matrix intersection $\mathbf{W}$ is deduced from the following equation:

$$\mathbf{W} = \mathbf{C} \cap \mathbf{C}^T$$

Matrix $\mathbf{W}$ has non-zero elements only in those places, where matrix $\mathbf{C}$ has non-zero elements as well as matrix $\mathbf{C}^T$. In this case matrix $\mathbf{W}$ takes the following form [10]:

$$\mathbf{W} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{array}{l} \text{-medium-pressure steam} \\ \text{-low-pressure steam 1} \\ \text{-low-pressure steam 2} \\ \text{-soft water} \\ \text{-boiler water} \\ \text{-industrial water} \end{array}$$

In the analysed example the intersection matrix $\mathbf{W}$ contains one strongly coherent subsystem involving the following energy carriers: medium-pressure steam, low-pressure steam 1, low-pressure steam 2 and boiler water. The other two branches (industrial water and soft water) do not compose a strongly coherent subsystem due to the lack of feedback connections. They correspond to zero-rows and zero-columns in the intersection matrix $\mathbf{W}$.

The order of rows and columns in the matrix $\mathbf{W}$ is the same as in Table 9.13. Rearranging the fourth and fifth row, as well as the fourth and fifth column, we obtain the matrix $\overline{\mathbf{W}}$ as a matrix with diagonally-arranged blocks:

$$\overline{\mathbf{W}} = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Table 9.15 Input-output binary matrix $(\mathbf{A}^b + \mathbf{F}^b)$ transformed into a block-triangular matrix with a minimal number of feedback elements.

Energy carrier	i \ j	1	2	3	4	5	6	7	8	9	10	11	12	13
Electrical energy	1	0	0	0	1	1	0	1	1	1	1	1	1	0
Power coal	2	0	0	0	0	0	0	0	1	0	0	0	0	0
Low-calorific gas	3	0	0	0	0	0	0	0	1	0	0	0	0	0
Industrial water	4	0	0	0	0	1	0	0	0	0	1	0	1	0
Soft water	5	0	0	0	0	0	0	1	0	0	1	1	0	0
Low-pressure steam 2	6	0	0	0	0	0	0	1	1	0	0	0	0	0
Boiler water	7	0	0	0	0	0	0	0	1	1	0	0	0	0
Medium-pressure steam	8	0	0	0	0	0	0	0	0	1	1	0	0	0
Low-pressure steam 1	9	0	0	0	0	0	1	0	0	0	1	1	0	0
Process air	10	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat	11	0	0	0	0	0	0	0	0	0	0	0	0	0
Compressed air	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Natural gas	13	0	0	0	0	0	0	0	0	0	0	0	0	0

The final form of the matrix $(\mathbf{A}^b + \mathbf{F}^b)$, after topological classification, is presented in Table 9.15. Below the main diagonal there is only one non-zero element corresponding to the coefficient of the consumption of low-pressure steam 1, used for the production of low-pressure steam 2. According to the arrangement of the rows in the topologically arranged matrix $(\mathbf{A}^b + \mathbf{F}^b)$, first the balances concerning the energy branches belonging to the output block are set up, beginning with natural gas. Next, the branches of the centre block are

balanced taking into account the iterative loop concerning the low-pressure steam 1 (feedback). The calculations are completed by the balance of electricity winding up the “input” block. As already mentioned, the balancing of the energy carriers, the determination of the coefficients of consumption a_{ij} and by-production f_{ij} , as well as the choice of energy equipment, are interdependent tasks. Therefore the presented sequence of balancing is simultaneously the sequence of choosing the energy equipment in the respective energy branches.

9.8.4. Input data

Figures 9.13 to 9.15 present the duration curves for the following energy carriers

- duration curves of the sale of low-pressure steam 1 - $\dot{K}_9(\tau)$ - Fig.9.13,
- duration curves of the global demand for heat - $\dot{Q}_{11}(\tau)$ - Fig. 9.14,
- duration curves of the global demand for compressed air - $\dot{G}_{12}(\tau)$ - Fig. 9.15.

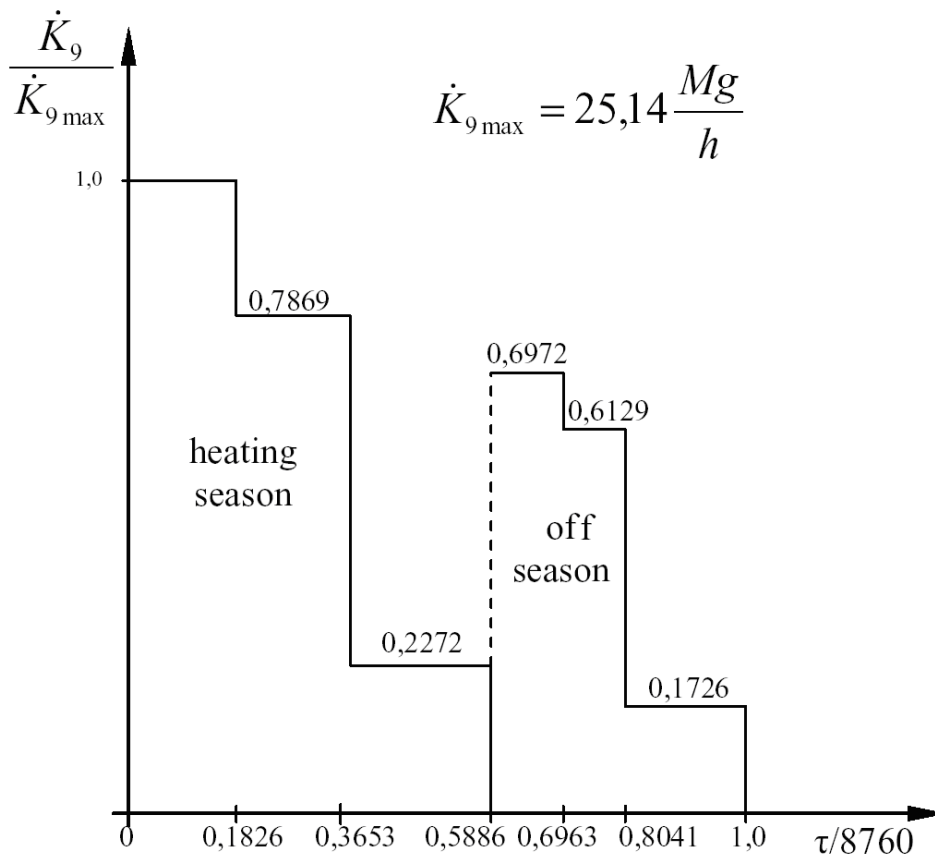


Fig. 9.13. Duration curve concerning the sale of low-pressure steam 1

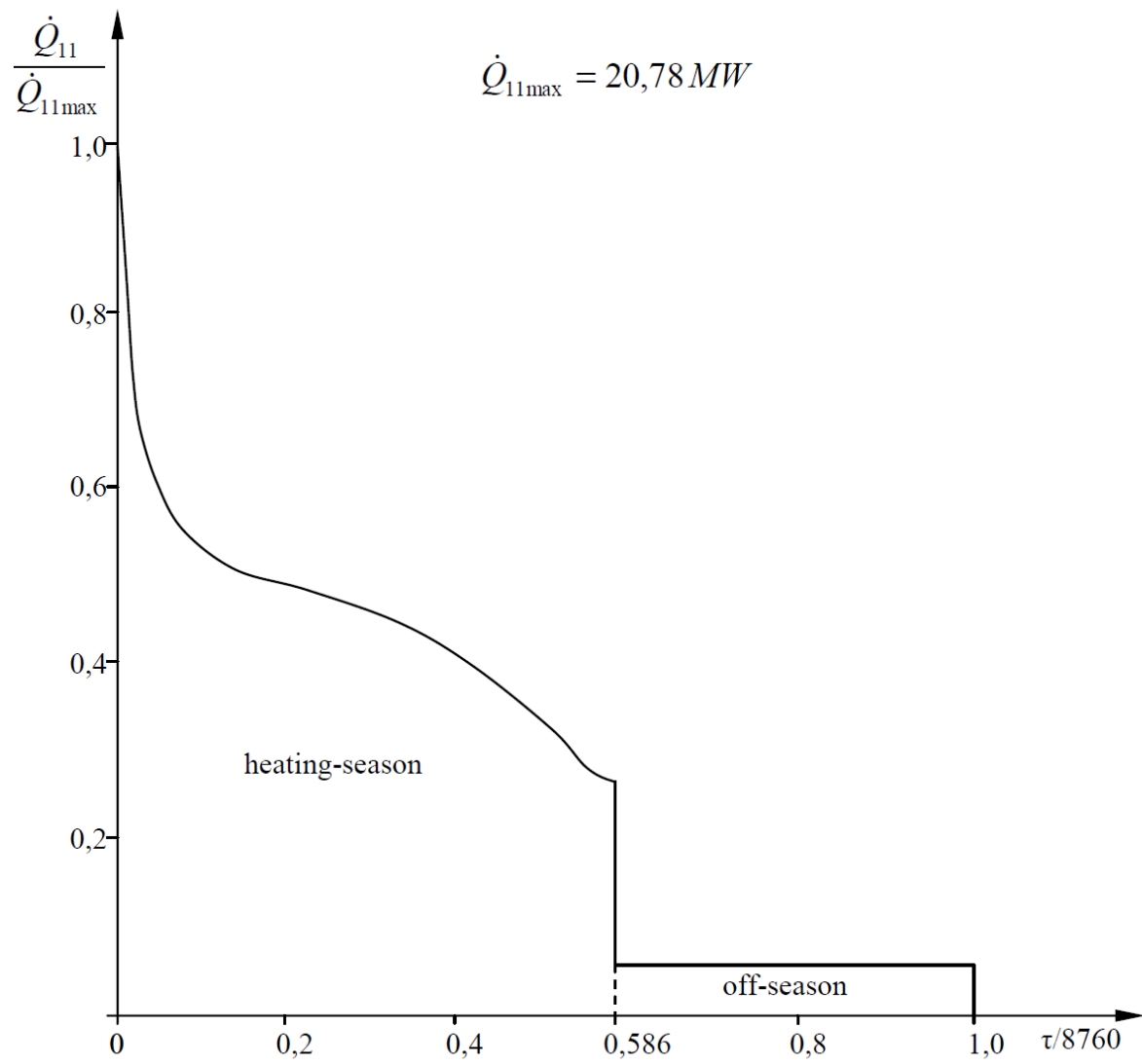


Fig. 9.14. Duration curve of the global demand for heat

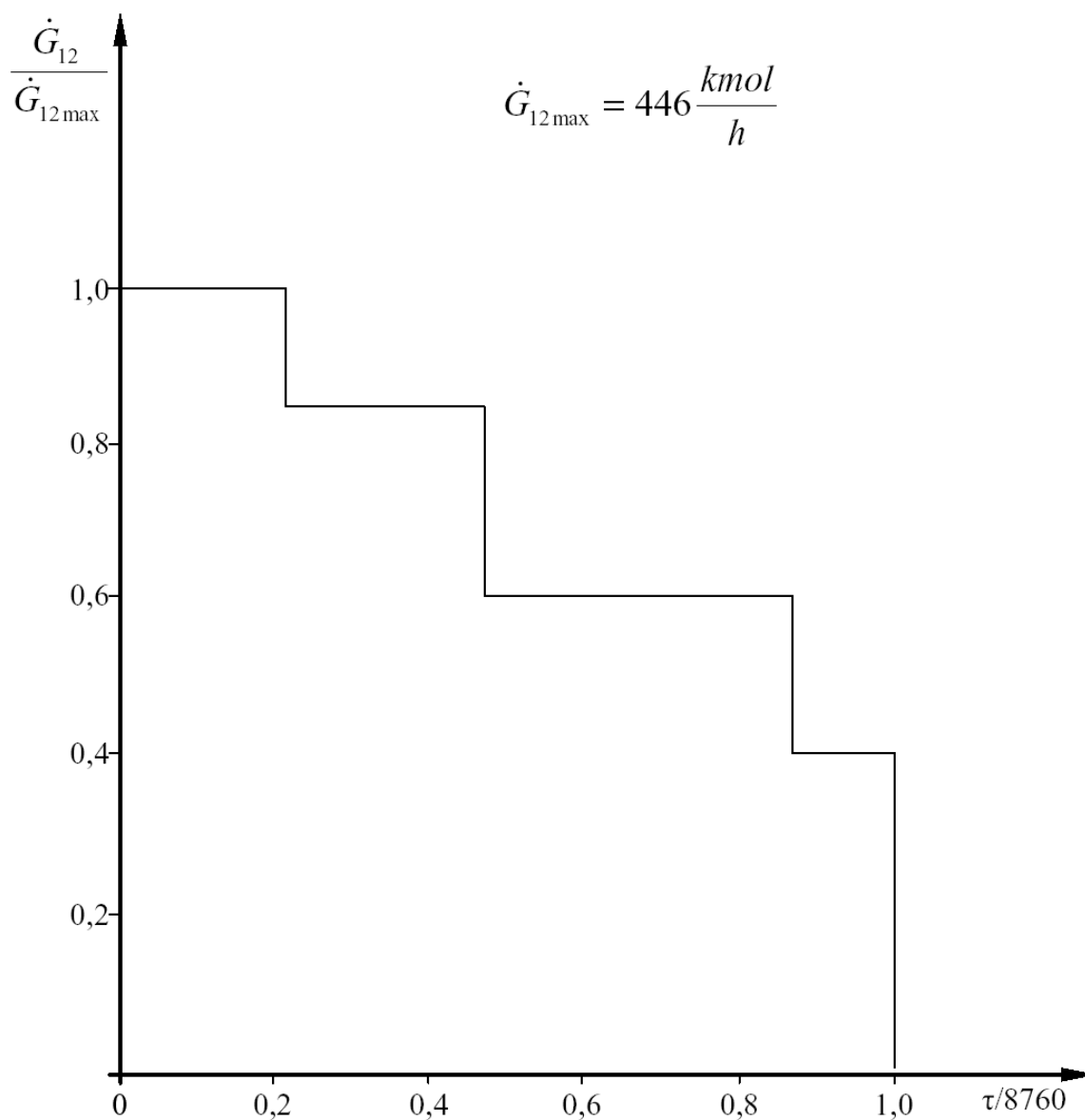


Fig. 9.15. Duration curve concerning the global demand for compressed air

Tables 9.16 and 9.17 present the first approximation of the unit costs of energy carriers, as well as the technical coefficients of the consumption and by-production of energy carriers for a strongly coherent subsystem.

Table 9.16 Unit costs of energy carriers – first approximation

i	Energy carrier	Unit	Average cost
1	Electrical energy	m.u. */MWh	1 850.0
2	Power coal	m.u./GJ	76.5
3	Low-calorific gas	m.u./ GJ	76.5

4	Industrial water	m.u./10 ³ Mg	580.0
5	Soft water	m.u./ Mg	85.0
6	Low-pressure steam 2	m.u./ Mg	238.0
7	Boiler water	m.u./ Mg	93.0
8	Medium-pressure steam	m.u./ Mg	265.0
9	Low-pressure steam 1	m.u./ Mg	252.0
10	Process air	m.u./Mmol	2 915.0
11	Heat	m.u./GJ	106.0
12	Compressed air	m.u./ Mmol	2 466.0
13	Natural gas	m.u./GJ	97.6

* m.u.- monetary unit

Table. 9.17. Coefficients of consumption and by-production of energy carriers for a strongly coherent subsystem – first approximation.

Energy carrier		Unit	Value	
			heating-season	off-season
Medium-pressure steam	a_{89}	Mg/Mg	0.9847	1.0000
Low-pressure steam 1	a_{96}	Mg/Mg	1.0000	1.0000
Low-pressure steam 2	f_{68}	Mg/Mg	0.0138	0.0138
	a_{67}	Mg/Mg	0.0875	0.0800
Boiler water	a_{78}	Mg/Mg	1.0600	1.0600
	a_{79}	Mg/Mg	0.0153	0.0000

The coefficients a_{89} and a_{79} are calculated from the following equations:

$$a_{89} = \frac{a_{89}^P P_9 + a_{89}^G G_9}{P_9 + G_9}, \quad (9.43)$$

$$a_{79} = \frac{a_{79}^G G_9}{P_9 + G_9} \quad (9.44)$$

where:

$a_{89}^P = 1$ - coefficient of the consumption of medium-pressure steam for the basic part of the production of low-pressure steam 1,

a_{89}^G - coefficient of the medium-pressure steam consumption by the pressure-reducing valve 3.7/0.8 MPa,

P_9, G_9 - basic and variable (peak) part of low-pressure steam 1 production,

a_{79}^G - coefficient of boiler water consumption by the pressure-reducing valve 3.7/0.8 MPa.

The coefficients a_{89}^G and a_{79}^G are calculated from the mass and energy balance of the pressure-reducing valve 3.7/0.8 MPa (Fig.9.12.):

$$a_{89}^G = \frac{h_9 - h_7}{h_8 - h_7}, \quad (9.45)$$

$$a_{79}^G = \frac{h_8 - h_9}{h_8 - h_7} \quad (9.46)$$

where: h_7 , h_8 and h_9 denote the specific enthalpy of boiler water, medium- and low-pressure steam 1, respectively.

The coefficient f_{68} of the by-production of low-pressure steam 2 is calculated from the mass and energy balance of the expander after the blowdown of the boiler (Fig 9.12)

$$f_{68}^G = \zeta \frac{h_8' - h_6'}{h_6'' - h_6'} \quad (9.47)$$

where:

ζ - ratio of amount of saline water for the blow-off to the production of medium-pressure steam,

h_8' , h_6' - specific enthalpy of saline water from the blow-off and thickened saline water from the expander, respectively,

h_6'' - specific enthalpy of saturated vapour from the expander (low-pressure steam 2).

Based on the mass and energy balances of the deaerated water (Fig 9.12) the coefficients a_{67}^G and a_{57}^G describing the consumption of soft water and low-pressure steam 2 for the production of boiler water, we obtain [16]:

$$a_{67}^G = \frac{1}{h_6 - h_5} \left[h_7 - h_5 + \frac{G_{cT}}{G_7} (h_5 - h_{cT}) + \frac{G_{10}}{G_7} f_{510}^G (h_5 - h_{cB}) + \frac{G_{11}}{G_7} f_{511}^G (h_5 - h_{cH}) \right] \quad (9.48)$$

$$a_{57}^G = 1 - a_{67}^G - \frac{1}{G_7} (G_{cT} + f_{510}^G G_{10} + f_{511}^G G_{11}) \quad (9.49)$$

where:

h_5 , h_6 , h_7 , - specific enthalpy of soft water, low-pressure steam 2 and boiler water, respectively,

G_{cT} - amount of condensate from the subsystem of industrial consumers,

G_7, G_{10}, G_{11} - production of boiler water, process air and heat, respectively,

f_{510}^G, f_{511}^G - coefficients of the by-production of condensate from turbo-blowers and heat exchangers, respectively,

h_{cT}, h_{cB}, h_{cH} – specific enthalpy of the condensate from the subsystem of industrial consumers, process air turbo-blowers and heat exchangers, respectively.

9.8.5. Algorithms for the determination of the optimal power rating and nominal capacity of the engines and energy equipment [19]

The order of energy carriers in Table 9.15 is final and obligatory in further calculations. The optimal power rating and capacity of the engines and energy equipment have been determined for each variant by means of Lagrange's method of decomposition. Individual optimisation algorithms for each energy carrier are employed.

A. Compressed air

The nominal capacities of air compressors and their number are determined by means of the comparison of variants. The following assumptions have been made:

- all the air compressors have the same nominal capacity,
- the maximum capacity of the air compressor assembly should cover the maximum demand of compressed air for the considered subsystem of consumers,
- additionally, one air compressor must be foreseen as a reserve.

The objective function for the comparison of the variants in this case takes the following form:

$$\Phi_{12} = (\rho_{G12} + \beta_{G12})I_{G12} + \alpha_{G12}\dot{G}_{n12} + (\varepsilon_{G12} + a_{112}^G k_1 + a_{412}^G k_4)G_{12} \rightarrow \min \quad (9.50)$$

where:

$\dot{G}_{n12}$ - nominal capacity of the air compressor assembly,

a_{112}^G, a_{412}^G - coefficients of the consumption of electrical energy and industrial water, respectively,

k_1, k_4 - average unit cost of electrical energy and industrial water,

G_{12} - annual production of compressed air.

Two variants are considered. The following data are identical for both variants:
pressure ratio – 8.8; $\rho_{G12} = 0.11$; $\beta_{G12} = 0.029$; $\varepsilon_{G12} = 291 \text{ m.u.}^* / \text{Mmol}$. The remaining data are presented in Table 9.18.

Table 9.18. Data and calculation results for the determination of the air-compressor assembly

Quantity	Unit	V a r i a n t	
		1	2
Nominal capacity	kmol/h	446	281
Power of electric motor	kW	1250	750
Number of compressors		2	3
Capital expenditure	mln m.u./year	88.4	92.09
$\alpha_{G12} \dot{G}_{n12}$	mln m.u./year	3.1	4.35
a_{112}^G	MWh/Mmol	2.6502	2.4821
a_{412}^G	10^3 Mg/Mmol	0.3475	0.3116
Φ_{12} (final iteration)	mln m.u./year	30.9	31.6

^{*)} *m.u.* - monetary unit

The results of the comparison of the considered variants are presented in Table 9.18. Variant 1 has been chosen for the design. A similar approach was applied in the case of the branch process air.

B. Low-pressure steam 1

Low-pressure steam 1 from the back-pressure steam turbine is the basic part of the production. The peak part of low-pressure steam production is obtained from the pressure-reducing valve 3.7/0.8 MPa. The objective function for calculating the optimal power rating of the back-pressure steam turbine has the following form:

$$\begin{aligned} \Phi_9 = & (\rho_{P9} + \beta_{P9})I_{P9} + (\rho_{G9} + \beta_{G9})I_{G9} + \alpha_{P9}\dot{P}_{n9} + \alpha_{G9}\dot{G}_{n9} + (\varepsilon_{P9} + \alpha_{49}^P k_4 + \alpha_{89}^P k_8 - f_{19}^P k_1)P_9 + \\ & + (\varepsilon_{G9} + \alpha_{79}^G k_7 + \alpha_{89}^G k_8)G_9 \rightarrow \min \end{aligned} \quad (9.51)$$

where:

I_{P9} , I_{G9} - investments outlay concerning back-pressure turbine and pressure-reducing valve station,

$\dot{P}_{n9}, \dot{G}_{n9}$ - flux of low-pressure steam 1 from the back pressure steam turbine with nominal load and nominal capacity of the pressure-reducing valve 3.7/0.8 MPa, respectively,
 P_9, G_9 - annual basic and peak part of low-pressure steam 1 production, respectively,
 a_{49}^P, a_{89}^P - coefficients of the consumption of industrial water and medium-pressure steam for the back-pressure steam turbine,
 $\alpha_{79}^G, \alpha_{89}^G$ - coefficients of the consumption of boiler water and medium-pressure steam for the pressure-reducing valve station,
 f_{19}^P - coefficients of the by-production of electric energy in the back-pressure steam turbine,
 k_1, k_4, k_7, k_8 - unit costs of electric energy, industrial water, boiler water and medium-pressure steam, respectively.

The algorithm for the determination of the power rating for the back-pressure steam turbine was formulated based on the following assumptions:

- all the electricity produced in the CHP plant is consumed by the considered subsystem of consumers; moreover the national electrical power system supplies the considered municipal-urban complex,
- the investment outlay for the steam-boiler house of the CHP plant does not depend on the power rating of the back-pressure steam turbine,
- the cost of repairs and maintenance, prime cost and operating costs (without the cost of energy carriers) do not depend on the power rating of the back-pressure steam turbine,
- the efficiency of the steam boiler is independent of the power rating of the back-pressure steam turbine,
- the pressure-reducing valve 3.7/0.8 MPa should secure the peak part of the production of low-pressure steam 1, and cover the demand for low-pressure steam 1 in case the back-pressure steam turbine should fail,
- the influence of the power rating of the pack-pressure steam turbine on the investment outlay of the pressure-reducing valve 3.7/0.8 MPa is inconsiderable,
- the influence of the power rating of the back-pressure steam turbine on the costs of boiler water for the steam boilers and pressure-reducing valve 3.7/0.8 MPa, as well as the cost of industrial water for the back-pressure steam turbine are also inconsiderable.

The objective function now takes the form:

$$\Phi_9 = (\rho_{p9} + \beta_{p9})I_{p9} + (\rho_{G9} + \beta_{G9})I_{G9} + \alpha_{p9}\dot{P}_{n9} + \alpha_{G9}\dot{G}_{n9} + \varepsilon_{p9}P_9 + \varepsilon_{G9}G_9 + (a_{49}k_4 + a_{79}k_7 + a_{89}k_8 - f_{19}k_1)\Omega_9 \rightarrow \min \quad (9.52)$$

where:

$$\Omega_9 = P_9 + G_9 \quad (9.53)$$

The values of the coefficients a_{79} , a_{89} are determined by means of the Eqs. (9.44), (9.43). The coefficients a_{49} and a_{19} are expressed similarly. Due to the assumption c), f) and g) the following term of the objective function is constant:

$$C_1 = \beta_{p9}I_{p9} + (\rho_{G9} + \beta_{G9})I_{G9} + \alpha_{p9}\dot{P}_{n9} + \alpha_{G9}\dot{G}_{n9} + \varepsilon_{p9}P_9 + \varepsilon_{G9}G_9 + (\alpha_{49}k_4 + \alpha_{79}k_7)\Omega_9 \quad (9.54)$$

Based on the balance of costs concerning the medium-pressure steam we get:

$$k_{G8} = \alpha_{18}k_1 + \alpha_{28}k_2 + \alpha_{38}k_3 + \alpha_{78}k_7 - k_{F6}f_{68} + \frac{S_8}{\Omega_8} \quad (9.55)$$

where:

$\Omega_8 = G_8$ - annual production of medium-pressure steam,

$f_{68} = f_{68}^G$ - coefficient of the by-production of low-pressure steam 2 (equation 9.47)),

$a_{18}, a_{28}, a_{38}, a_{78}$ - coefficients of the consumption of electrical energy, power coal, low-calorific gas and boiler water for the steam boilers,

$k_1, k_2, k_3, k_{F6}, k_7, k_{G8}$ - unit costs of electrical energy, power coal, low-calorific gas, by-production of low-pressure steam 2, boiler water and medium-pressure steam, respectively,

S_8 - arbitrary fixed costs (without the costs of energy carriers) of the steam boilers.

Introducing the expression (9.55) into equation (9.52) we obtain:

$$\Phi_9 = \rho_{p9}I_{p9} + (\alpha_{28}k_2 + \alpha_{38}k_3)\alpha_{89}\Omega_9 - k_1f_{19}\Omega_9 + C_2 \rightarrow \min \quad (9.56)$$

where:

$$C_2 = \left(\alpha_{18}k_1 + \alpha_{78}k_7 - f_{68}k_{F6} + \frac{S_8}{\Omega_8} \right) \alpha_{89}\Omega_9 + C_1. \quad (9.57)$$

The influence of the power rating of the back-pressure steam turbine on the term C_2 may be neglected.

The annual costs of the by-production of electrical energy is given by:

$$k_1f_{19}\Omega_9 = \frac{f_{19}\Omega_9}{\eta_{Epp}\eta_{et}}k_2 + K_{rem} \quad (9.58)$$

where:

η_{Epp} - energy efficiency of the production of electrical energy in the reference system electrical power station fired with hard coal,

η_{et} - efficiency of the transmission of electrical energy,

k_2 - unit cost of power coal,

K_{rem} - remaining costs (without the cost of hard coal) of the production of electricity in the replaced electrical power station.

The term K_{rem} has no influence on the optimal of power rating of the back-pressure steam turbine.

The following expressions have been introduced which denote consumption of the chemical energy of fuels in the boilers and the production of electricity:

$$(a_{28} + a_{38})a_{89}\Omega_9 = \frac{a_{89}\Omega_9\Delta i_9}{\eta_{Eb}} + E_{chel} \quad (9.59)$$

$$f_{19}\Omega_9 = E_{el} \quad (9.60)$$

where:

Δi_9 - decrease of specific enthalpy of low-pressure steam 1 supplied to consumers,

η_{Eb} - energy efficiency of steam boilers,

E_{chel} - annual consumption of the chemical energy of fuels in steam boilers burdening the production of electricity,

E_{el} - annual production of electricity in the back-pressure turbo-generator.

Introducing equations (9.58) to (9.60) into (9.56) and assuming that $k_2 = k_3$ (low calorific gas replaces hard coal with the same efficiency of boiler), we obtain:

$$\Phi_9 = \rho_{p9}I_{p9} + \left(E_{chel} - \frac{E_{el}}{\eta_{Epp}\eta_{et}} \right) k_2 + C \rightarrow \min \quad (9.61)$$

where:

$$C = C_2 + \frac{a_{89}\Omega_9\Delta i_9}{\eta_{Eb}} + K_{rem} \quad (9.62)$$

The influence of the power rating of the back-pressure steam turbine on the term C may be neglected.

The annual production of electrical energy E_{el} is determined from the equation:

$$E_{el} = N_{el\ n} \tau_n + \int_{\tau_n}^{\tau_a} N_{el} d\tau \quad (9.63)$$

where:

$N_{el\ n}, N_{el}$ - power rating and instantaneous value of the load of the back-pressure turbo-generator,

τ_n, τ_a - annual duration of operation of the turbo-generator with power rating load and the annual action duration of the turbo-generator.

The annual consumption of the chemical energy of fuels in the steam boilers for the production of electrical energy is given by:

$$E_{ch\ el} = \frac{1}{\eta_{Eb}} \left[\frac{N_{el\ n}}{\eta_{me\ n}} \tau_n + \int_{\tau_n}^{\tau_a} \frac{N_{el}}{\eta_{me}} d\tau \right] \quad (9.64)$$

where $\eta_{me\ n}, \eta_{me}$ denote the electromechanical efficiency of the turbo-generator with power rating load, as well as with instantaneous load.

The investment outlay characteristic for back-pressure turbine is given by the following equation:

$$I_{pg} = a_T c_T c_n N_{el\ n}^{0.7} \quad (9.65)$$

where:

a_T - coefficient dependent on the thermodynamic parameter of incoming steam,

c_T - unit capital expenditure for the back-pressure steam turbine, m.u./MW,

c_n - coefficient dependent on the number of turbo-generators.

Figure 9.16. presents the duration curve concerning the global demand for low-pressure steam 1. The duration curve is divided into two parts: heating season and off-season.

The power rating of the back-pressure steam turbine is calculated from the following equation:

$$N_{el\ n} = \dot{P}_{9\max} \Delta h_T \eta_{in} \eta_{men} \quad (9.66)$$

where:

$\dot{P}_{9\max}$ - maximum flux of exhaust steam from the back-pressure steam turbine,

Δh_T - isentropic decrease of specific enthalpy in the back-pressure steam turbine,

η_{in} - nominal isentropic efficiency of the back-pressure steam turbine.

The efficiencies η_{in} and $\eta_{me n}$ are calculated form the following empirical [12] equations:

$$\eta_{in} = -0.1531N_{eln}^{-0.914} + 0.853 \quad (9.67)$$

$$\eta_{me n} = 0.0126N_{eln} + 0.856 \quad (9.68)$$

Based on the energy characteristics of the back-pressure steam turbine [16], the electrical power N_{el} is determined:

$$N_{el} = \frac{\dot{P}_9 - Xd_n N_{eln}}{(1 - X)d_n} \quad (9.69)$$

and

$$d_n = \frac{1}{\Delta h_T \eta_{in} \eta_{me n}} \quad (9.70)$$

where:

$\dot{P}_9$ - flux of exhaust steam from the back-pressure steam turbine,

X - coefficient of idle run of the turbo-generator.

The coefficient X and electromechanical efficiency η_{me} are calculated from the following equations [12]:

$$X = 0.0041N_{eln}^2 - 0.0465N_{eln} + 0.342 \quad (9.71)$$

$$\eta_{me} = \eta_{me n} \left[1 - 0.646 \left(1 - \frac{N_{el}}{N_{eln}} \right)^2 + 1.745 \left(1 - \frac{N_{el}}{N_{eln}} \right)^4 - 2.099 \left(1 - \frac{N_{el}}{N_{eln}} \right)^6 \right] \quad (9.72)$$

The optimal power rating of the back-pressure steam turbine is determined based on the condition:

$$\phi = \rho_{p9} a_T c_T c_n N_{eln}^{0.7} + k_2 \left\{ \frac{1}{\eta_{Eb}} \left[\frac{N_{eln}}{\eta_{me n}} \tau_n + \int_{\tau_n}^{\tau_a} \frac{N_{el}}{\eta_{me}} d\tau \right] - \frac{1}{\eta_{E pp} \eta_{et}} \left[N_{eln} \tau_n + \int_{\tau_n}^{\tau_a} N_{el} d\tau \right] \right\} \rightarrow \min \quad (9.73)$$

Equation (9.73), as well as the auxiliary expressions (9.67) to (9.72) constitute the algorithm for the determination of the optimal power rating of the back-pressure steam turbine. The duration curve concerning the global demand for low-pressure steam 1 (Fig. 9.19) is the fundamental set value. Other data are: $\eta_{Epp} = 0.34$; $\eta_t = 0.96$; $k_2 = 76.5 \text{ m.u./GJ}$; $\eta_{Eb} = 0.78$; $a_T = 1$; $c_T = 25 \text{ m.u./MW}$; $c_n = 1$; $\rho_T = 0.11$; thermodynamic variable of medium pressure-steam: $p = 3 \text{ MPa}$, $t = 435^\circ \text{C}$; pressure of exhaust steam from the back-pressure steam turbine -0.8 MPa ; and temperature of condensate from the process and heat exchangers -80°C .

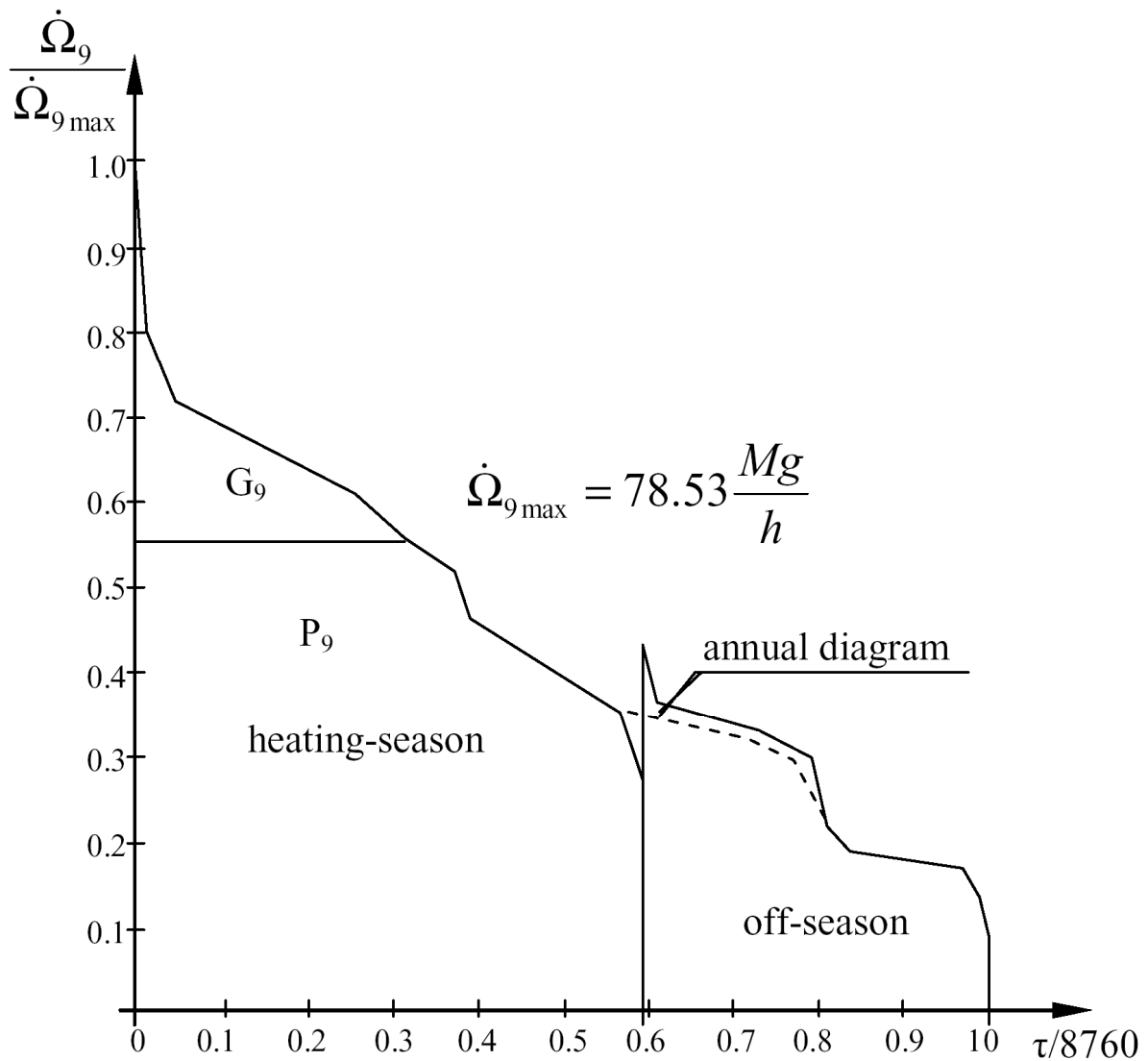


Fig. 9.16. Duration curve concerning the global demand for low-pressure steam 1

It has been calculated, that this optimal power rating of the back-pressure steam turbine is $N_{el\ n\ opt} = 3.45 MW$. Figure 9.16 shows the field, covered by low-pressure steam 1 from the back-pressure steam turbine (P_9), as well as the field covered by steam from the reducing-pressure valve 3.7/0.8 MPa (G_9). The coefficient f_{19}^P of the by-production of electrical energy is calculated from the following equation:

$$f_{19}^P = \frac{1}{P_9} (N_{el\ n\ opt} \tau_{n\ opt} + \int_{\tau_{n\ opt}}^{\tau_q} N_{el} d\tau) \quad (9.74)$$

The coefficient a_{49}^P of the consumption of industrial water was determined on the basis of catalogue data for a back-pressure steam turbine.

C. Medium-pressure steam

Variant III of this energy management system foresees the installation of steam boilers fired with low-calorific gas (fundamental fuel) and hard coal.

The choice of steam boilers is made by comparing the following variants:

- 1) three steam boilers with a maximum capacity of 30 Mg/h,
- 2) three steam boilers with a maximum capacity of 35 Mg/h,
- 3) three steam boilers with a maximum capacity of 40 Mg/h,
- 4) four steam boilers with a maximum capacity of 30 Mg/h,

The following assumptions have been made:

- a) the prime cost depends on the number of steam boilers,
- b) the maximum fraction of chemical energy of power coal in the fuel mixture is 50 per cent,
- c) the repair of steam boilers is foreseen in the off-season, and the idle time for repair concerns only one steam boiler.

The objective function has the following form:

$$\Phi_8 = (\rho_{G8} + \beta_{G8}) I_{G8} + \alpha_{G8} \dot{G}_{n8} + (\varepsilon_{G8} + a_{18}^G k_1 + a_{28}^G k_2 + a_{38}^G k_3 + a_{78}^G k_7 - f_{68}^G k_{F6}) \cdot G_8 \rightarrow \min \quad (9.75)$$

where:

$\dot{G}_{n8}$ - nominal capacity of the steam boilers,

G_8 - annual production of the steam boilers,

$a_{18}^G, a_{28}^G, a_{38}^G, a_{78}^G$ - coefficient of the consumption of electrical energy, power coal, low-calorific gas and boiler water, respectively,

f_{68}^G - coefficient of the by-production of low-pressure steam 2,

k_1, k_2, k_3, k_7 - average unit costs of electrical energy, power coal, low-calorific gas and boiler water, respectively,

k_{F6} - unit cost of the by-production of low-pressure steam 2.

The costs of losses due to failures of the boilers are presented in Table 9.19. In the case of the failure of a steam boiler first of all the turbo-blowers are turned off, and blowers with direct drive are turned on.

The following data are used in the calculations:

- investment outlay characteristics of steam boilers:

$$I_{G_8} = a_b c_b (0.25 n_8^{-0.3} + 0.75) n_8 \dot{G}_{n8}^{0.65} \quad (9.76)$$

where:

a_b - coefficient dependent on the thermodynamic parameters of steam; $a_k = 1$ for $p = 3.7$ MPa and $t = 450^\circ\text{C}$,

c_b - unit capital expenditure for the steam boiler; ($c_k = 45$ mln m.u./Mg)

n_8 - number of steam boilers,

$\dot{G}_{n8}$ - nominal capacity of boiler

- energy efficiency characteristics of steam boiler:

$$\eta_{Eb} = 0.307 z_g^2 - 0.361 z_g + 0.848 \quad (9.77)$$

where z_g denotes the share of chemical energy of low-calorific gas in the fuel mixture,

- maximum capacity characteristics of the steam boiler

$$\dot{G}_{8\max} = \dot{G}_{8\max o} (1 - 0.4 z_g) \quad (9.78)$$

where $\dot{G}_{8\max o}$ denotes the maximum capacity in the case of a coal-fired steam boiler.

In order to determine the coefficients a_{28}^G and a_{38}^G , concerning the consumption of hard coal and low-calorific gas the following data must be known:

- duration curve $G_8(\tau)$ of the demand for medium-pressure steam (Fig. 9.17),
- energy characteristics of a steam boiler,
- duration curve of the chemical energy of the fuel mixture $\dot{E}_{ch}(\tau)$.

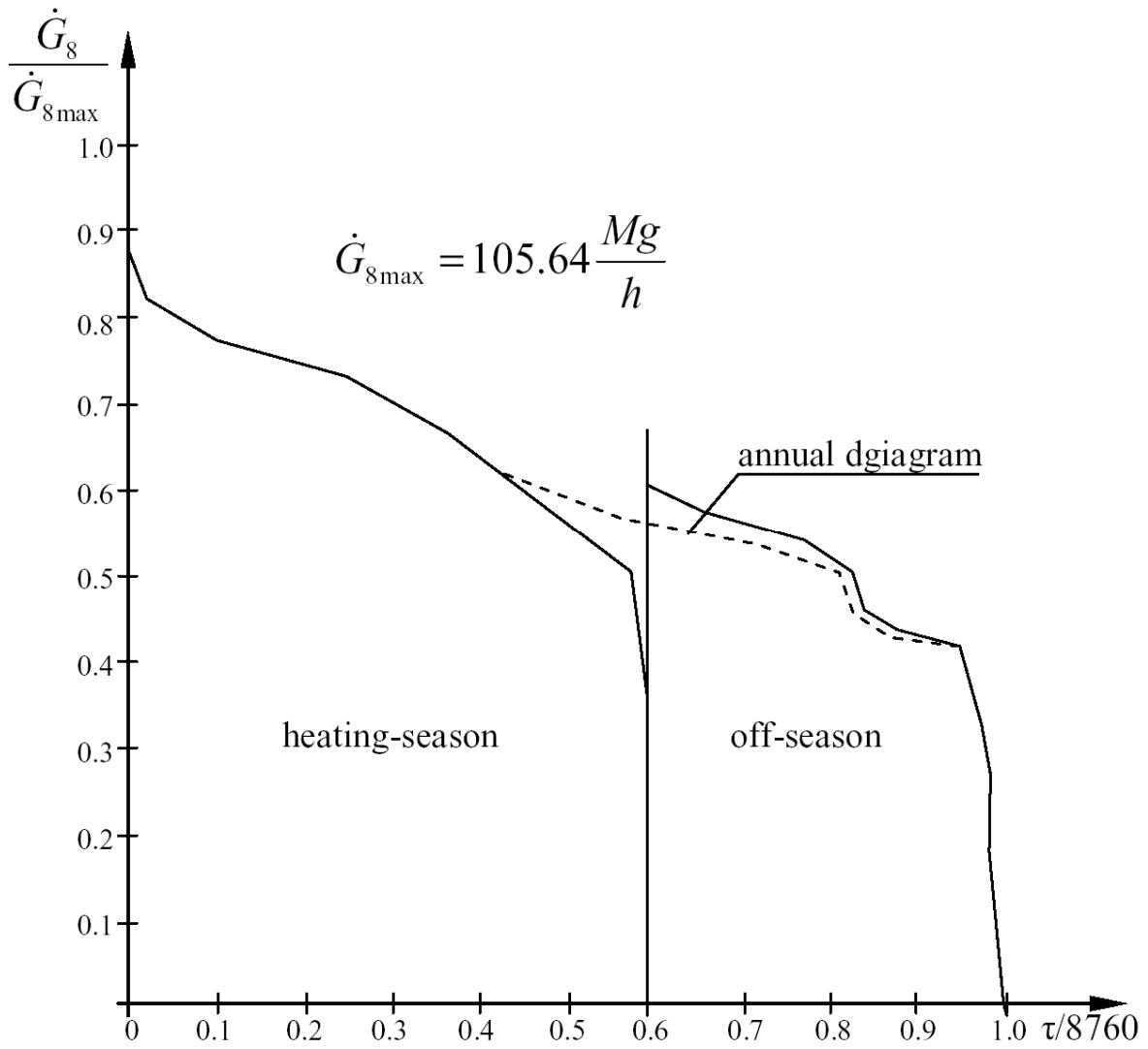


Fig. 9.17. Duration curve concerning the global demand for medium-pressure steam

Using equation (9.77) the energy characteristic of a steam boiler has the following form:

$$\dot{E}_{ch} = \frac{\dot{G}_8 \Delta h_8}{0.307 z_g^2 - 0.361 z_g + 0.848} \quad (9.79)$$

where

$\dot{E}_{ch}$ - the flux of chemical energy of the fuel mixture,

$\dot{G}_8$ - flux of the production of medium-pressure steam,

Δh_8 - increase of specific enthalpy in the boiler.

Introducing equation (9.78) into the energy characteristics (9.79) we obtain a right-side limitation of this characteristic:

$$\dot{E}_{ch\max} = \frac{\dot{G}_{8\max}(1-0.4z_g)\Delta h_8}{0.307z_g^2 - 0.361z_g + 0.848}. \quad (9.80)$$

Surplus amounts of low-calorific gas are passed into double fuel boilers. The forecast demands for fuel for double-fuel boilers can be analysed based on forecasts of the duration curves of the surplus of low-calorific fuel gas and the demand for live steam, as well as the energy characteristics of a double fuel boiler.

Figure 9.18 presents the method of determining the demand for chemical energy E_{chg} of low-calorific gas, as well as the chemical energy E_{chc} of hard coal for the steam boilers. The coefficients a_{28} and a_{38} are calculated from the equations:

$$a_{28} = \frac{E_{chc}}{G_8} \quad (9.81)$$

$$a_{38} = \frac{E_{chbg}}{G_8} \quad (9.82)$$

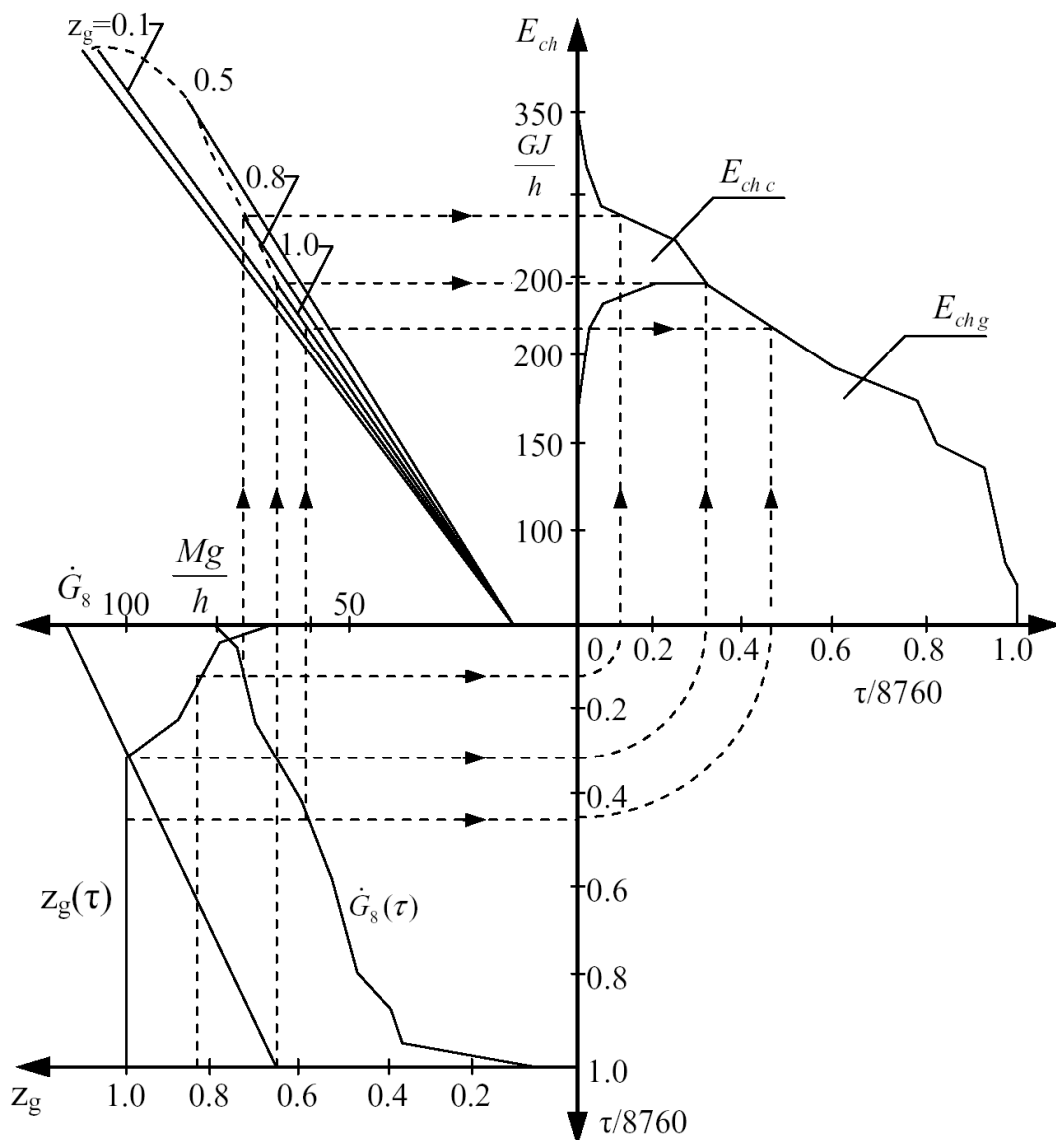


Fig. 9.18 Method of determining the demand for chemical energy of low-calorific gas and the chemical energy of power coal for the steam boilers [24]; E_{chg} - chemical energy of low-calorific gas; E_{chc} - chemical energy of hard coal

Figure 9.18 presents a full example of the forecasting analysis of the management of fuels in double-fuel boilers [24]. The bottom left-hand corner in Figure 9.18 contains the duration curve $\dot{G}_8(\tau)$ of the demand for live steam and the dependence of the maximum capacity of the boilers on the share of the chemical energy of low-calorific gas in the total chemical energy of fuels. Based on both these diagrams the diagram of the changing share of the chemical energy of low-calorific gas in the chemical energy of fuels was set up corresponding to the changes in the demand for steam in compliance with the duration curve

$\dot{G}_8(\tau)$. In the upper left-hand corner the energy characteristics of a double-fuel boiler house are shown. The characteristics comprise a set of segments of straight lines concerning various shares z_g of low-calorific gas, which is a characteristic parameter. On the characteristic a line has been plotted limiting the family of straight lines on the right-hand side.

Based on the duration curve $\dot{G}_8(\tau)$ expressing the demand for live steam and on the energy characteristics of the double-fuel boilers the duration curve of the consumption of the chemical energy of fuel mix has been plotted. This duration curve is to be seen in the upper right-hand corner of Figure 9.18, where also the curve $E_{ch\ g}$ describing the consumption of the surplus low-calorific gas, is also shown. The deficiency of the chemical energy of low-calorific gas must be compensated by combustion of an additional amount of hard coal $E_{ch\ c}$.

The values of the coefficients a_{18}^G, a_{58}^G and f_{68}^G have been determined based on information obtained by practical experience concerning the exploitation of double-fuel steam boilers.

Table 9.19. Data and calculation results concerning the nominal capacity of steam boilers

Quantity	Unit	V a r i a n t			
		1	2	3	4
Nominal capacity	Mg/h	30	35	40	30
Number of steam boilers		3	3	3	4
$(\rho_{G8} + \beta_{G8})I_{G8}$	mln m.u./year	193.1	213.4	232.7	256.3
$\alpha_{G8}\dot{G}_{n8}$	mln m.u./year	15.7	15.7	15.7	17.1
K_{T8}	mln m.u./year	75.4	58.2	39.7	19.2
a_{28}^G	GJ/Mg	0.3117	0.1442	0.0751	0.0751
a_{38}^G	GJ/Mg	3.3699	3.4772	3.6221	3.6221
Φ_8 (final iteration)	mln m.u./year	568.4	564.7	558.2	563.8

*) m.u. - monetary unit

The nominal capacity of steam boilers has been determined by comparing four variants. The results of the comparison of the considered variants are presented in Table 9.19. Variant three has been chosen for design.

D. Boiler water

The nominal capacities of boiler water pumps and their number are determined by means of the comparison of variants. The maximum capacity $\dot{G}_{7\max}$ of the pumping station for boiler water should satisfy the following inequality:

$$\dot{G}_{7\max} \geq a_{78}^G \dot{G}_{8\max} + a_{79} \dot{\Omega}_{9\max} \quad (9.83)$$

where:

$\dot{G}_{8\max}, \dot{\Omega}_{9\max}$ - maximum flux of medium-pressure steam and low-pressure steam 1, respectively,

a_{78}^G, a_{79} - coefficients of the consumption of boiler water for steam boilers and the pressure-reducing valve 3.7/0.8 MPa.

In this example:

$$\dot{G}_{7\max} \geq 136.15 \text{ Mg} / \text{h}$$

The aim function has the following form:

$$\Phi_7 = (\rho_{G7} + \beta_{G7}) I_{G7} + \alpha_{G7} \dot{G}_{n7} + (\varepsilon_{G7} + a_{17}^G k)_1 G_7 \rightarrow \min \quad (9.84)$$

where:

$\dot{G}_{n7}$ - nominal capacity of the pumping station for boiler water,

G_7 - annual production of boiler water,

a_{17}^G - coefficient of the consumption of electrical energy.

The following assumptions have been made:

- all the boiler water pumps have the same nominal capacity,
- the capacity of a boiler water pumping station should not reduce the capacity of the steam boiler,
- additionally, one boiler water pump must be foreseen as a stand-by pump and two additional pumps driven by diesel-engines are foreseen,
- the operating costs without the cost of electrical energy are the same for all the variants.

Three variants have been considered. The following data are identical for these variants:

$$\rho_{G7} = 0.114$$

$$\beta_{G7} = 0.029$$

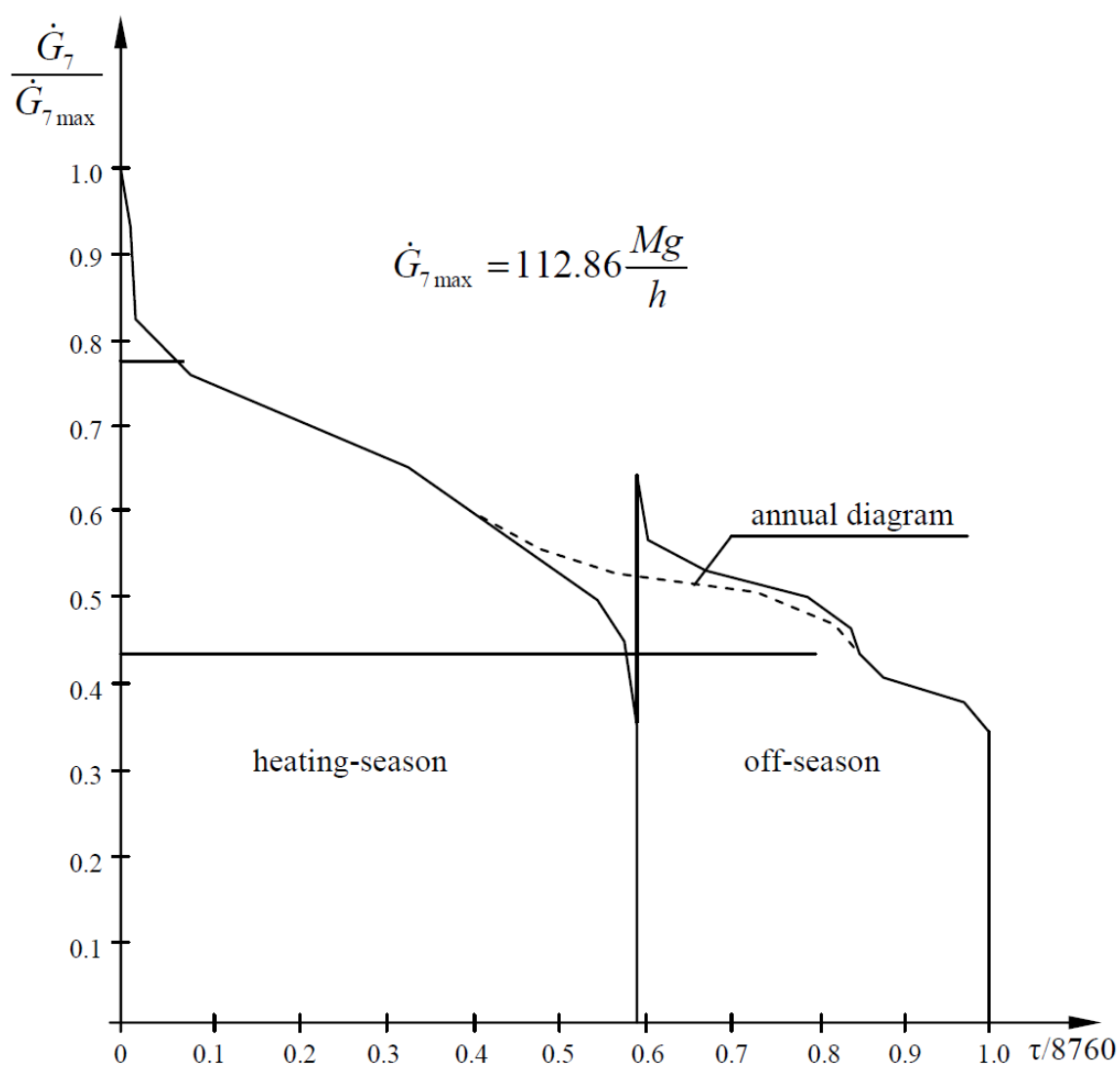


Fig. 9.19 Duration curve of the global demand for boiler water

Table 9.20 Data and calculation results of the nominal capacity of boiler-water pumps

Quantity	Unit	V a r i a n t		
		1	2	3
Nominal capacity	Mg/h	27	45	75
Number of pumps		5	3	2
Driving power of electric motor	MW	0.08	0.16	0.20
Capital expenditure	mln m.u.*	10.9	8.1	7.0
$\alpha_{G7} \dot{G}_{n7}$	mln m.u./year	4.0	2.7	2.7
a_{17}^G	MWh/ 10^3 Mg	0.00312	0.00276	0.00294
Φ_7 (final iteration)	mln m.u./year	8.83	6.71	6.75

*) m.u. - monetary unit

Based on the duration curve of the demand for boiler water (Fig. 9.19) the considered variants have been analysed. The energy characteristics of the boiler water pump assembly have been taken into account. The results of the comparison of the variants are presented in Table 9.20. Variant 2 has been chosen for design.

D. Electrical energy

Electrical energy is used to cover the needs of the subsystem of consumers of the industrial-urban complex and the internal needs of the energy subsystem. The duration curve of the global demand for electrical energy from the national electrical power system is presented in Figure 9.20. This diagram has been set up taking into account the by-production of electrical energy by the back-pressure steam turbine.

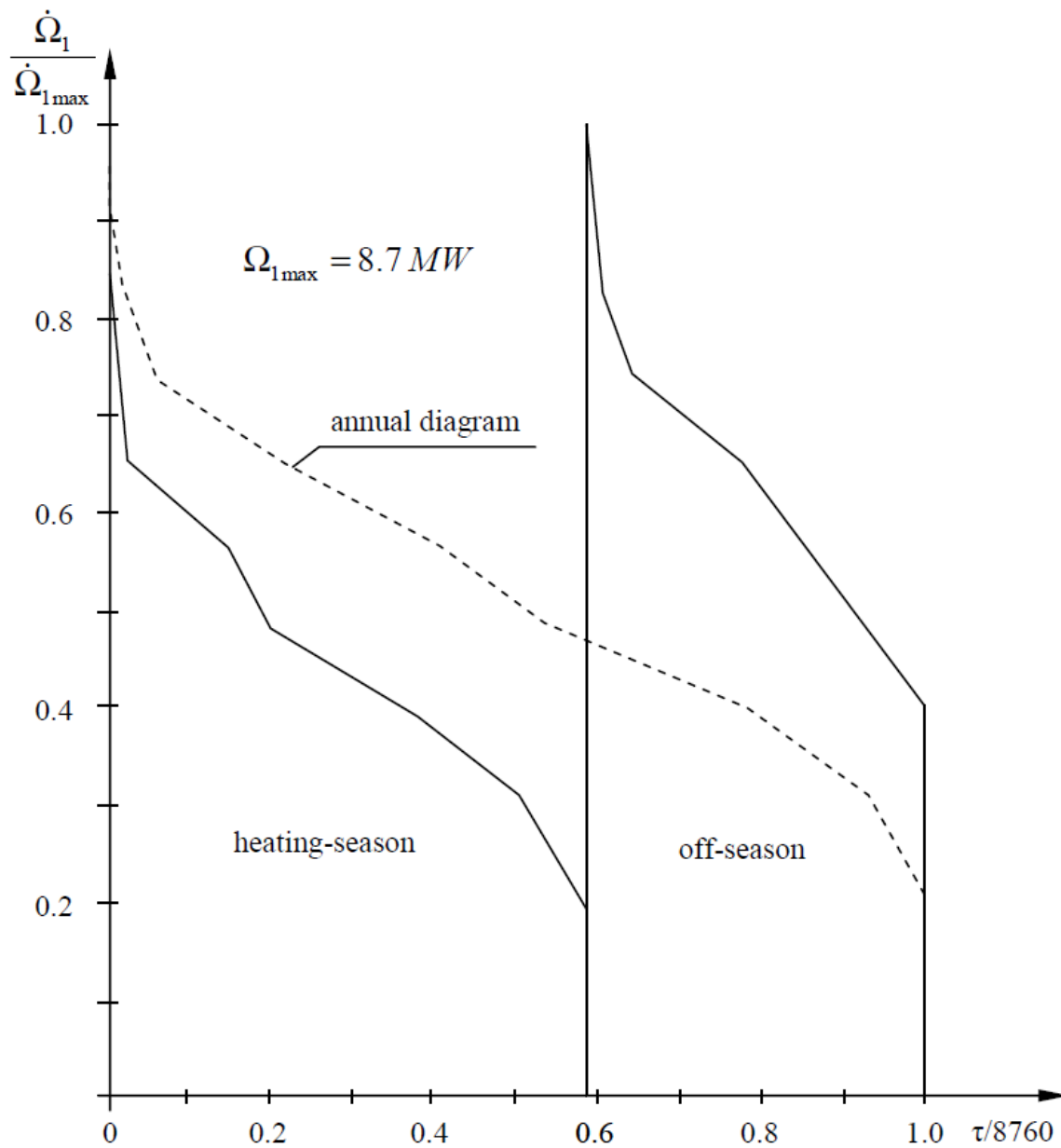


Fig. 9.20 Duration curve concerning the global demand for electrical energy from the national electrical power system

9.8.6. Calculation procedure and results [16,22]

Calculations concerning the choice of the optimal structure of the energy management of the industrial-urban complex are an iterative procedure resulting from the applied decomposition of the global problem of optimisation by means of Lagrange's method. The requirement of the compliance of the global criterion with local criteria (objective functions for particular energy

carriers) is satisfied by the procedure of coordination, that is, the matrix method of determining the unit costs of energy carriers.

Table 9.21. Technical coefficients of the consumption and by-production of energy carriers in the energy subsystem (final iteration)

i	Energy carrier	Consumer branch	Sym bol	Unit	Value of coefficient
1	Electric energy	Boilers	a_{18}	MWh/Mg	0.0031
		Turbo-generator	a_{19}	MWh/Mg	0.0785
		Turbo-blowers	a_{110}	MWh/Mmol	0.0157
		Heat exchangers	a_{111}	MWh/GJ	0.0017
		Water softening plant	a_{15}	MWh/Mg	0.0010
		Pumping station for boiler water	a_{17}	MWh/Mg	0.0028
		Pumping station for industrial water	a_{14}	MWh/ 10^3 Mg	0.0900
		Air compressor	a_{112}	MWh/Mmol	2.6502
2	Power coal	Steam boilers	a_{28}	GJ/t	0.0751
3	Low-calorific gas	Steam boilers	a_{38}	GJ/t	3.6221
4	Industrial and drinking water	Turbo-generator	a_{49}	10^3 Mg/Mg	0.0007
		Turbo-blowers	a_{410}	10^3 Mg/Mmol	0.4971
		Water softening plant	a_{45}	10^3 Mg/Mg	0.0010
		Air compressor	a_{412}	10^3 Mg/Mmol	0.3475
5	Soft water	Turbo-blowers	f_{510}	10^3 Mg/Mmol	4.8842
		Heat exchangers	f_{511}	Mg/GJ	0.4000
		Pumping station of boiler water	a_{57}	Mg/Mg	0.8921
6	Low-pressure steam 2	Steam boilers	f_{68}	Mg/Mg	0.0138
		Pumping station of boiler water	a_{67}	Mg/Mg	0.1979
7	Boiler water	Steam boilers	a_{78}	Mg/Mg	1.0600
		Turbo-generator	a_{79}	Mg/Mg	0.0080
8	Medium-pressure steam	Turbo-generator and pressure-reducing valve 3.7/0.8 MPa	a_{89}	Mg/Mg	0.9920
		Turbo-blowers	a_{810}	Mg/Mmol	4.9839
9	Low-pressure steam 1	Pressure-reducing valve 0.8/0.12 MPa	a_{96}	MJ/Mg	1.0000
		Turbo-blowers	a_{910}	Mg/Mmol	0.4590
		Heat exchangers	a_{911}	Mg/GJ	0.4131

The coefficients of the consumption and by-production of energy carriers (final iteration) are collated in Table 9.23. Based on data provided in catalogues of energy equipment issued by the producers, five coefficients have been assumed, viz. a_{15}, a_{18}, a_{110} of the consumption of electrical energy when soft water is being produced, as well as a_{49} and a_{412} which express the consumption of industrial water when low-pressure steam 1 and compressed air are being produced. The values of the coefficients a_{17} and a_{112} of the consumption of electrical energy driving the boiler-water pumps and air compressors, as well as the coefficient a_{810} of the consumption of medium-pressure steam driving the blowers

were determined based on the characteristics of the power equipment and the duration curves of the demand for energy carriers. The coefficients a_{28} and a_{38} were determined by means of a forecasting analysis of the consumption of fuel in steam boilers. The values of the coefficients a_{57} and a_{67} of the consumption of soft water and low-pressure steam 2 are determined based on the deaereating heater balance. From the balance of the pressure-reducing valves, the values of the coefficients of the consumption of medium-pressure steam and boiler water are derived, whereas from the balance of the expander after the blowdown of the boiler, the coefficient f_{68} of the by-production of low-pressure steam 2 in the steam boilers is derived. The coefficient f_{19}^P of the by-production of electrical energy by a back-pressure steam turbine is determined by means of individual algorithms. The values of the coefficients a_{47}, a_{79}, a_{89} and f_{19} are determined after the division of the production of steam by the back-pressure turbine and the pressure-reducing valve 3.7/0.8 MPa. The remaining technical coefficients were evaluated based on the practical experience obtained from the existing energy subsystems (e.g., industrial water and heat).

The power rating and capacity of the engines and energy equipment have been determined each time in the iterative loop of the coordination process (the outer iterative loop of the investigated variant). In the case of energy branches constituting a strongly coherent subsystem it was necessary to select the equipment in the iterative loop comprising the determination of the values of the coefficients of consumption and by-production of energy carriers (interior iterative loop). In the example in question, four iterations had to be made within the process of determining the unit costs of energy carriers (Table 9.21). In each outer iterative loop, three iterations were accomplished in the interior loop of the strongly coherent subsystem. Calculations in the interior iterative loop are brought to an end as soon as the required accuracy in the determination of the coefficients of consumption and by-production of energy carriers has been achieved. In the quoted example an accuracy of $\varepsilon = 0.005$ has been assumed. The value ε corresponds to the accuracy in the solution of the balance equations of energy carriers amounting to about 0.3 per cent.

Table 9.22. Ratio of unit coasts in the last and first iteration

t	Energy carrier	Ratio of unit costs in the last and first iteration
1	Electrical energy	1

2	Power coal	1
3	Low-calorific gas	1
4	Industrial water	1
5	Soft water	1.36
6	Low-pressure steam 2	2.96
7	Boiler water	2.26
8	Medium-pressure steam	2.89
9	Low-pressure steam 1	2.76
10	Process air	1.81
11	Heat	2.59
12	Compressed air	3.81
13	Natural gas	1

Calculations in the outer iterative loop are completed when the required accuracy in the determination of the unit cost of energy carriers has been reached. In this example it was assumed that $\nu = 0.005$. A better accuracy of calculations does not affect the choice of the optimal power and capacity of engines and energy equipment.

Table 9.23. Power rating or nominal capacity, annual production and external supplies

t	Energy carrier	Power rating or nominal capacity	Annual production and external supplies
1	Electrical energy	3,45 MW	65285 ¹⁾ MWh
2	Power coal		39600 GJ
3	Low-calorific gas		4819 TJ
4	Industrial water	6000 Mg/h	47800 Gg
5	Soft water	40 Mg/h	231900 Mg
6	Low-pressure steam 2	15 Mg/h	53300 Mg
7	Boiler water	135 Mg/h	561300 Mg
8	Medium-pressure steam	120 Mg/h	527150 Mg
9	Low-pressure steam 1	35 Mg/h	328050 ²⁾ Mg
10	Process air	6960 kmol/h	40300 Mmol
11	Heat		180000 GJ
12	Compressed air	892 kmol/h	2940 Mmol
13	Natural gas		376300 GJ

1) - own production – 25 800 MWh

2) - basic part of the production (back-pressure turbine - 306 000 Mg)

As a result of calculations of the choice of the optimal power rating and number of energy equipment concerning the variant presented in Figure 9.12, the optimal set of engines and energy equipment could be determined (Table 9.22). The boiler house was equipped with three steam boilers with a nominal capacity of 40 Mg/h each, and is fired with low-calorific

gas and hard coal. A back-pressure steam turbine was selected with a power rating of 3.45 MW. The peak production of low-pressure steam 1 is achieved in a set of three pressure-reducing valves 3.7/0.8 MPa with a nominal capacity of 35 Mg/h each. Low-pressure steam 2 is produced in a pressure-reducing valve 0.8/0.12 MPa with a capacity of 15 Mg/h. Two axial-flow blowers were selected with a capacity of 3.480 kmol/h, driven by condensation turbines with a power rating of 4.25 MW each. In the designed air-compressor assembly the installation of two radial compressors with a nominal capacity of 446 kmol/h has been chosen. In the boiler-water pumping station four pumps are installed with a capacity of 45 Mg/h each (one of them is to be a stand-by pump).

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Appendix A

Selected elements of Boolean algebra and set theory

Boolean algebra is one part of mathematical logics. All Boolean functions may be constructed applying the following elementary functions:

- a) $\bar{x}$ - negation; negation denotes that $\bar{x} = 0$ if $x = 1$ and $\bar{x} = 1$ if $x = 0$
- b) $x \wedge y$ - conjunction (logical multiplication); the result of logical multiplication equals 1 only if $x = 1$ and $y = 1$; in all other cases it equals zero; the symbol $\wedge$ means “and”,
- c) $x \vee y$ - alternatives (logical addition); the result of logical addition is equal to zero only if $x = 0$ and $y = 0$; in all other cases it equals one; the symbol $\vee$ means “or”,

Set theory deals with investigations concerning the properties of sets. The notion “set” is indefinable and belongs to primary conceptions. Sets are denoted either by capital Latin letters or by braces $\{ \}$ including the symbols of all the elements of the set. The elements of the sets are denoted by small Latin letters. A set which does not include any element is an empty set denoted by the symbol $\emptyset$.

If the element a belongs to the set A , then:

$$a \in A$$

Otherwise, we have:

$$a \notin A$$

The symbol:

$$a \in^{\wedge} A$$

means : every a belongs to the set A .

If every element of the set B belongs also to the set A , then the set B is a subset of the set A :

$$B \subset A$$

Otherwise, it is expressed as:

$$B \not\subset A$$

If A and B are arbitrary sets, the sum of these sets is:

$$A \cup B = \{x: x \in A \vee x \in B\} \tag{A.1}$$

This set consists only of those elements which belong to at least one of these sets.

The difference between the sets A and B or the complement of the set B to the set A is called a set of elements belonging to A but not belonging simultaneously to B :

$$A \setminus B = \{x: x \in A \wedge x \notin B\} \quad (\text{A.2})$$

The logical product of the sets A and B is:

$$A \cap B = \{x: x \in A \wedge x \in B\} \quad (\text{A.3})$$

This set consists of elements belonging to both of these sets.

The Cartesian product of the sets A and B is a set of all arranged pairs (a,b) in which in the first place there is an element of set A and in the second place an element of the set B :

$$A \times B = \{(a, b): a \in A \wedge b \in B\}, \quad (\text{A.4})$$

The symbol $\times$ denotes the Cartesian product. Just as the Cartesian product of two sets can be defined, so also can generalised Cartesian products of numerous sets. For example the product $R \times R \times R$, where R is a set of all real numbers, denotes a three-dimensional space (3D).

Appendix B

Elements of the matrix calculus

A matrix is an arranged specification of a set of elements (numbers). A matrix with the dimensions $m \times n$ is a set composed of $m \times n$ elements arranged in the shape of a rectangle containing n rows and m columns, denoted as:

$$\mathbf{A} = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \quad (\text{B.1})$$

where:

$i = 1, 2, \dots, m$ - number of rows

$j = 1, 2, \dots, n$ - number of columns.

The quantities a_{ij} are elements of the matrix. The first index denotes the number of the row, the second the number of the column, in which the given element is to be found. If the number of rows equals the number of columns, we have a square matrix. The set of elements in the square matrix, where $i = j$, is called the main diagonal of the matrix.

A matrix consisting of one element:

$$\mathbf{A} = [a]$$

is a number.

A matrix consisting of one row:

$$\mathbf{A} = [a_1 \ a_2 \dots a_n] \quad (\text{B.2})$$

is called a row vector (row matrix).

A matrix consisting of one column:

$$\mathbf{A} = \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ b_n \end{bmatrix} \quad (\text{B.3})$$

is called a column vector (column matrix). The vector is a specific case of a matrix.

A matrix in which all the elements are zeros is called a null matrix denoted by the symbol $\mathbf{0}$.

A square matrix, in which all the elements above or below the main diagonal are equal to zero, i.e. the matrix:

$$\mathbf{A} = \begin{bmatrix} a_{11} & 0 & \dots & 0 \\ a_{21} & a_{22} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (\text{B.4})$$

or

$$\mathbf{B} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ 0 & b_{22} & \dots & b_{2n} \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & b_{nn} \end{bmatrix} \quad (\text{B.5})$$

is called a triangular matrix. The matrix $\mathbf{A}$ is a bottom triangular matrix and $\mathbf{B}$ an upper triangular matrix.

A square matrix with all the elements beyond the main diagonal ($i \neq j$) being equal to zero, i.e. the matrix:

$$\mathbf{C} = \begin{bmatrix} c_{11} & 0 & \dots & 0 \\ 0 & c_{22} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & c_{nn} \end{bmatrix} \quad (\text{B.6})$$

is a diagonal matrix.

A diagonal matrix in which all the elements along the main diagonal are equal to 1, is called an identity matrix, denoted as:

$$\mathbf{I} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1 \end{bmatrix} \quad (\text{B.7})$$

The square matrix is symmetrical if:

$$a_{ij} = a_{ji}$$

concerning all i and j . This means that the elements on both sides of the main diagonal are equal in their absolute value and sign. The elements of the main diagonal of the symmetric matrix may have any given value.

Two matrices are considered to be equal if the number of the rows and columns is equal and if the corresponding elements of both matrices are equal.

The acute inequality of two matrices with the same dimensions, e.g.:

$$\mathbf{A} > \mathbf{B}$$

denotes, that

$$a_{ij} > b_{ji}$$

concerning all i and j .

The inacute inequality e.g. $\mathbf{A} \geq \mathbf{B}$ of two matrices with the same dimensions comprises cases when $a_{ij} > b_{ji}$ concerning the same i -values and j -values, as well as $a_{ij} > b_{ij}$ concerning other i -values and j -values.

For inacute inequalities double symbols are used, viz.:

$$\mathbf{A} \geq \mathbf{B}$$

when the case $\mathbf{A} = \mathbf{B}$ is excluded.

The sum of two matrices $\mathbf{A}$ and $\mathbf{B}$ with an equal number of rows and columns is the matrix $\mathbf{C}$ whose elements are equal to the sums of the corresponding elements in the matrices $\mathbf{A}$ and $\mathbf{B}$:

$$\mathbf{C} = \mathbf{A} + \mathbf{B}, \tag{B.8}$$

if

$$c_{ij} = a_{ij} + b_{ij}$$

concerning all i and j .

This definition may, of course, be extended to the sums of more than two matrices. The summing of matrices with different dimensions is nonsensical. The summing of matrices is subject to the laws of commutativity and connexion, viz.:

$$\mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$$

and

$$\mathbf{A} + (\mathbf{B} + \mathbf{C}) = (\mathbf{A} + \mathbf{B}) + \mathbf{C}$$

If to any arbitrary matrix $\mathbf{A}$ a null matrix is added, the sum of the matrices is the same as that of matrix $\mathbf{A}$. That means, the null matrix behaves similarly as zero among the algebraic digits.

The product of the number “ p ” and the matrix $\mathbf{A}$ or the matrix $\mathbf{A}$ and number “ p ” results from the matrix $\mathbf{A}$ by multiplying all its elements by the number “ p ”. In some particular cases the following may occur:

$$1 \cdot \mathbf{A} = \mathbf{A} \cdot 1 = \mathbf{A}$$

$$0 \cdot \mathbf{A} = \mathbf{A} \cdot 0 = \mathbf{0}$$

Multiplying the matrix **A** by the number (-1) the reverse matrix $-\mathbf{A}$ is obtained, i.e. the matrix **A** in which the signs of all the elements have been changed.

The subtraction of two matrices with the same dimensions consists, therefore, in the addition of the first matrix to the matrix reverse versus to the second one:

$$\mathbf{A}-\mathbf{B}=\mathbf{A}+(-\mathbf{B}) \quad (\text{B.9})$$

In the particular case:

$$\mathbf{A}-\mathbf{A}=\mathbf{A}+(-\mathbf{A})=\mathbf{0}$$

The product **AB** of the matrix **A** and the matrix **B** can be determined only if the number of columns in the matrix **A** equals the number of rows in the matrix **B**, i.e. the matrix **A** is in agreement with the matrix **B**. If the matrices:

$$\begin{array}{c} k \text{ columns} \\ \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1k} \\ a_{21} & a_{22} & \dots & a_{2k} \\ \dots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & \dots & a_{ik} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mk} \end{bmatrix} \end{array} \quad \text{and} \quad \begin{array}{c} \mathbf{B} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1j} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2j} & \dots & b_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{k1} & b_{k2} & \dots & b_{kj} & \dots & b_{kn} \end{bmatrix} \end{array} \begin{array}{c} k \text{ rows} \end{array}$$

are given, the product of the matrices **AB** is the matrix

$$\begin{array}{c} n \text{ columns} \\ \mathbf{C} = \mathbf{A} \mathbf{B} = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \dots & \dots & \dots & \dots \\ c_{m1} & c_{m2} & \dots & c_{mn} \end{bmatrix} \end{array} \begin{array}{c} m \text{ rows} \end{array}$$

With the dimensions $m \times n$, whose elements c_{ij} are calculated basing on the relation:

$$c_{ij} = a_{i1} b_{1j} + a_{i2} b_{2j} + \dots + a_{ik} b_{kj}. \quad (\text{B.10})$$

Figure A.1. presents Falk's diagram of multiplying two matrices.

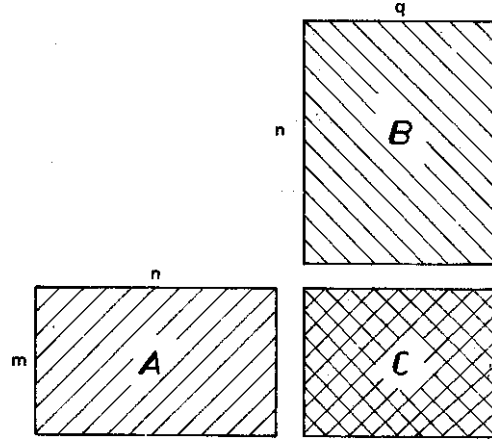


Fig.A.1. Falk's diagram of multiplying two matrices

In the particular case of multiplying the matrix **A** by the column vector **D** we get:

$$\mathbf{A} \mathbf{D} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ \dots \\ d_n \end{bmatrix} = \begin{bmatrix} a_{11}d_1 + a_{12}d_2 + \dots + a_{1n}d_n \\ a_{21}d_1 + a_{22}d_2 + \dots + a_{2n}d_n \\ \dots \\ a_{m1}d_1 + a_{m2}d_2 + \dots + a_{mn}d_n \end{bmatrix} \quad (\text{B.11})$$

In the case of each two square matrices with the same dimensions the product of the matrices is determined, resulting in a square matrix of the same dimension. In a particular case the product of two rectangular matrices may yield a square matrix.

The condition of the existence of the product of many matrices may be illustrated by the example of three matrices **A**, **B**, **C**. In order to obtain the product **ABC** (in the given sequence), **A** must agree with **B** and next **(AB)** with **C**.

The product of the matrices **A** and **B** is, generally, not commutative. The products **AB** and **BA** are not always equal, and it may even happen that one of these products does not exist at all, although the other one is being determined, e.g.:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \quad \text{and} \quad \mathbf{B} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

In such a case the product **AB** exists, whereas **BA** is not being determined.

The products of the matrices are jointed. If matrix **A** agrees with **B**, and **B** agrees with **C**, we get:

$$\mathbf{A} (\mathbf{B} \mathbf{C}) = (\mathbf{A} \mathbf{B}) \mathbf{C} . \quad (\text{B.12})$$

In the matrix calculus the law of divisibility of multiplying versus addition is also satisfied. If the matrix **A** agrees with **B** and **C** (**AB** and **AC** do exist) and if the dimensions of the matrices **B** and **C** are the same, then:

$$\mathbf{A}(\mathbf{B}+\mathbf{C}) = \mathbf{AB}+\mathbf{AC}. \quad (\text{B.13})$$

The identity matrix plays the same role in the multiplication of the matrix as unit in the multiplication of numbers, because:

$$\mathbf{A} \mathbf{I} = \mathbf{I} \mathbf{A} = \mathbf{A}, \quad (\text{B.14})$$

where **I** has an adequate dimension. If the dimension of matrix **A** is $m \times n$, then **I** must have the dimension $n \times n$ in the case of **A I**, but $m \times m$ in the case of **I A**. This consideration indicates that in any arbitrary place of the arbitrary product of the matrix an identity matrix may be introduced without changing the product, e.g. **IAB** = **ABI**, and all these matrices are equal to **AB**. In the particular case when **A** is a square matrix and the identity matrix **I** has the same dimensions as **A**, the law of commutativity is satisfied, because then the products **A I** and **I A** are equal.

The transposed matrix relating to **A** is such a matrix obtained from the primary matrix **A** by interchanging the rows for columns and the columns for rows:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

$$\mathbf{A}^T = \begin{bmatrix} a_{11} & a_{21} & \dots & a_{m1} \\ a_{12} & a_{22} & \dots & a_{m2} \\ \dots & \dots & \dots & \dots \\ a_{1n} & a_{2n} & \dots & a_{mn} \end{bmatrix} \quad (\text{B.15})$$

In special cases the transposed matrix of the row vector:

$$\mathbf{B} = [b_1 \ b_2 \ \dots \ b_n]$$

becomes a column vector

$$\mathbf{B}^T = \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ b_n \end{bmatrix}$$

A transposed matrix related to a transposed matrix is a primary matrix:

$$(\mathbf{A}^T)^T = \mathbf{A} \quad (\text{B.16})$$

Transposition of the sum:

$$(\mathbf{A} + \mathbf{B})^T = \mathbf{A}^T + \mathbf{B}^T, \quad (\text{B.17})$$

when $\mathbf{A}$ and $\mathbf{B}$ are matrices with the same dimensions.

Transposition of the product:

$$(\mathbf{A} \mathbf{B})^T = \mathbf{B}^T \mathbf{A}^T, \quad (\text{B.18})$$

where the matrix $\mathbf{A}$ agrees with the matrix $\mathbf{B}$.

Both these properties may be generalised concerning any number of matrices. In the case of the identity matrix:

$$\mathbf{I}^T = \mathbf{I} \quad (\text{B.19})$$

In the case of a symmetric matrix:

$$\mathbf{A} = \mathbf{A}^T \quad (\text{B.20})$$

To each square matrix a given number is strictly assigned, called the determinant of this matrix.

Square matrix:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

Determinant of matrix **A**:

$$|\mathbf{A}| = \begin{vmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix}$$

The minor of the given determinant of the degree n is a determinant of the degree $(n-1)$ obtained by crossing out, for example the i -th row and the j -th column. The co-factor D_{ij} of the element a_{ij} of the determinant is the number obtained by multiplying the respective minor by $(-1)^{i+j}$.

The square matrix of which the determinant equals zero is called singular matrix. Otherwise the matrix is called non-singular matrix.

By crossing out a certain number of rows and columns in the rectangular or square matrix, various square matrices can be obtained. The determinants of these matrices are called determinants achieved from the given matrix. The highest degree of the determinant differing from zero obtained from the given matrix is the rank “ r ” of this matrix.

The inverse matrix related to the square matrix **A** is the matrix $\mathbf{A}^{-1}$ when:

$$\mathbf{A}^{-1} \mathbf{A} = \mathbf{A} \mathbf{A}^{-1} = \mathbf{I}. \quad (\text{B.21})$$

The dimensions of the identity matrix **I** are the same as those of matrix **A**. The inverse matrix $\mathbf{A}^{-1}$ of the square matrix occurs only if the matrix **A** is a non-singular matrix, viz.: $|\mathbf{A}| \neq 0$.

The product of the given square matrix and its inverse matrix is commutative, as can be seen in (B.21). The inverse matrix of the inverse matrix is equal to the primary matrix, viz.:

$$(\mathbf{A}^{-1})^{-1} = \mathbf{A}. \quad (\text{B.22})$$

Reciprocal of the product:

$$(\mathbf{A} \mathbf{B})^{-1} = \mathbf{B}^{-1} \mathbf{A}^{-1}. \quad (\text{B.23})$$

Relation (B.23) concerns any number of matrices.

Inverse matrix related to a transposed matrix:

$$(\mathbf{A}^T)^{-1} = (\mathbf{A}^{-1})^T. \quad (\text{B.24})$$

The determinant of the inverse matrix is expressed by the relation:

$$|\mathbf{A}^{-1}| = \frac{1}{|\mathbf{A}|} \quad (\text{B.25})$$

The inverse matrix related to the identity matrix $\mathbf{I}$ is the same matrix $\mathbf{I}$. The inverse matrix related to the triangular bottom or upper matrix is respectively a bottom or upper triangular matrix.

If the given square matrix is a non-singular matrix, its inverse matrix A^{-1} equals:

$$\mathbf{A}^{-1} = \frac{\mathbf{D}^T}{|\mathbf{A}|} \quad (\text{B.26})$$

where:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} - \text{given square matrix of the row } r = n,$$

$$\mathbf{D} = \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \dots & \dots & \dots & \dots \\ D_{n1} & D_{n2} & \dots & D_{nn} \end{bmatrix} - \text{matrix obtained from the co-factors of the elements of the}$$

matrix A .

The matrix notation permits the set of “n” linear equations and transformations to which this set is subjected to be conveniently expressed. The set of “n” linear equations with n unknown values $x_1, x_2, \dots, x_n$ takes the form:

[illegible]

Introducing the matrix notation we can simply write:

$$\mathbf{A} \mathbf{X} = \mathbf{B} \tag{B.28}$$

where:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \text{ - matrix of coefficients,}$$

$$\mathbf{X} = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} \text{ - vector of unknown values,}$$

$$\mathbf{B} = \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ b_n \end{bmatrix} \text{ - free term vector.}$$

If the matrix $\mathbf{A}$ is a non-singular matrix (then an inverse matrix $\mathbf{A}^{-1}$ thus exist), by multiplying left-hand side matrix equation by $\mathbf{A}^{-1}$ we get:

$$\mathbf{A}^{-1} \mathbf{A} \mathbf{X} = \mathbf{A}^{-1} \mathbf{B},$$

$$\mathbf{X} = \mathbf{A}^{-1} \mathbf{B}. \quad (4.31)$$

In this way, by applying the inverse matrix, the given set of linear equations is solved. Although the solution of sets of linear equations by means of inverse matrices renders exact results, in the case of a large number of unknown values it is very laborious. In practice, when exact results are not required, a solution can be achieved faster by applying approximated methods. The application of inverse matrices is practically feasible if in the case of an unchanged matrix A of the coefficients solutions are required concerning various variants of the vector B on the right hand-side of the set of equations.

Appendix C

Algorithmic guidelines to exergy analysis

Exergy is a measure of quality of energy. It expresses the maximum work output attainable in the natural environment or a minimum work input necessary to realise the reverse process.

The exergy of substance consists of the following components:

$$B_s = B_k + B_p + B_f + B_{ch} \quad (C.1)$$

where:

B_k, B_p – kinetic and potential exergy; practically equal to the kinetic and potential energy

B_f, B_{ch} – physical and chemical exergy.

The sum of physical and chemical exergy is called thermal exergy. It is the basic component of exergy of the substance mostly applied in the exergy analysis of thermal processes:

$$B_t = B = B_{ph} + B_{ch} \quad (C.2)$$

Exergy does not satisfy the law of conservation and for this reason the exergy balance in real processes does not close. The difference between input and output exergy expresses the internal exergy losses. The so-called “exergy balance” is as follows:

$$B_d = \Delta B_s + B_o + \sum \Delta B_q + W + \delta B_i \quad (C.3)$$

where:

B_d, B_o – exergy delivered and carried out with the streams of matter,

ΔB_s – increase of exergy of the system,

ΔB_q – increase of exergy of the heat sources,

W – electrical or mechanical work performed by the system,

δB_i – internal exergy losses calculated in compliance with Gouy-Stodola’s law,

$$\Delta B_s = B_{sf} - B_{si} \quad (C.4)$$

i, f – initial and final state of the system,

$$B_o = B_{up} + B_{wp} \quad (C.5)$$

B_{up} – exergy of useful products,

B_{wp} – exergy of waste products.

External exergy losses are expressed by means of the exergy waste products or the unused component of exergy of a useful product (e.g. physical enthalpy of coke).

$$\delta B_{ex} = B_{wp} \quad (C.6)$$

The exergy of the system (exergy of the substance inside the balance shield) is calculated by a relation similar to Gibbs's formula:

$$B_s = B - V(p - p_a) \quad (C.7)$$

where:

B – exergy of the streams of matter calculated as input or output exergy,

V – volume of the system,

p, p_{ot} – pressure inside the system and ambient pressure.

The exergy increase of the heat source results from the Carnot efficiency:

$$\Delta B_q = -Q \frac{T - T_a}{T} \quad (C.8)$$

where:

Q – heat extracted from an external heat source,

T – temperature of the heat source,

T_a – ambient temperature.

Internal exergy losses (Gouy-Stodola's Law)

$$\delta B_i = T_a \sum \Delta S \quad (C.9)$$

Internal exergy losses determined in compliance with Gouy-Stodola's Law are irretrievable losses and cannot even be partly recovered. Thus, in the case of processes consisting of several parts the internal exergy losses can be calculated by summing up the internal exergy losses of the particular parts. Every exergy loss contributes to an increased consumption of input energy in the process or to a decrease of useful effects. Although in real processes exergy losses are inevitable, they should be restricted as far as technically possible and economically feasible. Losses of exergy are admissible only if they are indispensable for reducing the investment costs. If the loss of exergy is economically unjustified, it is an error in the art of engineering (the so-called Second Law error).

Calculation of specific thermal exergy:

$$b_t = b = b_{ph} + b_{ch} \quad (C.10)$$

$$b_{ph} = b_{phT} + b_{php} \quad (C.11)$$

where:

b_{ph} , b_{ch} – specific physical and chemical exergy, respectively,

b_{phT} – the temperature-dependent part of specific physical exergy,

b_{php} – the pressure-dependent part of specific physical exergy.

The temperature-dependent part of specific physical exergy is calculated from the relations:

$$b_{phT} = \Delta i_p \Big|_{T_a}^T - T_a \Delta s_p \Big|_{T_a}^T \quad (C.12)$$

or

$$b_{phT} = \int_{T_a}^T \frac{T - T_a}{T} di_p = \Delta i_p \Big|_{T_a}^T \frac{T_m - T_a}{T_m} \quad (C.13)$$

$$T_m = \frac{\Delta i_p \Big|_{T_a}^T}{\Delta s_p \Big|_{T_a}^T} \quad (C.14)$$

where:

$\Delta i_p \Big|_{T_a}^T$, $\Delta s_p \Big|_{T_a}^T$ – isobaric increase of enthalpy and entropy,

T_m – thermodynamic average temperature.

The pressure-dependent part of specific physical exergy:

$$b_{php} = \int_{p_a}^p v_a dp \quad (C.15)$$

In the case of ideal gases we get:

$$b_{php} = RT_a \ln \frac{p}{p_a} \quad (C.16)$$

In the case of solid or liquid substances:

$$b_{php} = v_a (p - p_a) \quad (C.17)$$

where v_a denotes the specific volume concerning the ambient temperature.

Specific chemical exergy of gaseous substances containing only gaseous reference species is calculated from the equation:

$$b_{ch} = T_a \sum_i g_i R_i \ln \frac{z_i}{z_{ia}} \quad (C.18)$$

In general the chemical exergy is estimated according to thermodynamic tables.

$$b_{ch} \cong b_{chn} \quad (C.19)$$

where:

b_{chn} – standard chemical exergy (thermodynamic tables).

The exergy efficiency of processes is generally calculated as follows:

$$\eta_B = \frac{B_{up}}{B_i} \quad (C.20)$$

where:

B_{up} – exergy of useful product (exergy of substance, mechanical or electrical work),

B_{in} – input exergy.

In the case of technological product we get:

$$\eta_{Bp} = \frac{\sum_i B_{up\,i} - \sum_k B_{snk}}{Pb_f + E_{el}} \quad (C.21)$$

where:

$B_{up\,i}$ – exergy of the „i-th” useful product,

$B_{sn\,k}$ – exergy of the „k-th” non-energy raw material,

P, b_f – consumption of fuel and specific exergy of fuel,

E_{el} – electrical energy.

Exergy efficiency of the thermal cycle:

Engine –
$$\eta_{Be} = \frac{\eta_{Ee}}{\eta_{Ee\,max}} \quad (C.22)$$

where:

η_{Ee} – energy efficiency of a real engine,

$\eta_{Ee\,max}$ – maximum energy efficiency of the engine (Carnot cycle),

Heat pump –
$$\eta_{hp} = \frac{COP_{hp}}{COP_{hp\,max}} \quad (C.23)$$

Refrigerator –
$$\eta_r = \frac{COP_T}{COP_{T\,max}} \quad (C.24)$$

where:

COP_{hp}, COP_r – coefficient of the performance of heat pump and refrigerator,

$COP_{hp\max}, COP_{r\max}$ – maximum coefficient of the performance of heat pump and refrigerator operating according to the Carnot cycle.

Exergy losses in typical irreversible processes

Hydraulic and mechanical friction:

$$\delta B = \frac{T_a}{T} Q_f \quad (C.25)$$

where:

Q_f – heat of friction,

T – temperature of the body absorbing the heat of friction.

Heat transfer:

$$\delta B = T_a Q \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \quad (C.26)$$

where:

Q – amount of transferred heat,

T_1, T_2 – temperature of the warmer and colder medium.

Throttling:

$$\delta \dot{B} = -\dot{G} T_a \int_{p_1}^{p_2} \frac{v}{T} dp \quad (C.27)$$

where:

$\dot{G}$ – flux of the medium,

v – specific volume,

p_1, p_2 – pressure before and after throttling.

Isobaric mixing of the substances without changing their composition:

$$\delta \dot{B} = T_a \left(\dot{C}_1 \ln \frac{T_m}{T_1} + \dot{C}_2 \ln \frac{T_m}{T_2} \right) \quad (C.28)$$

where:

$\dot{C}_1, \dot{C}_2$ – fluxes of heat capacity of substance 1 and 2,

T_1, T_2 – temperature of substance 1 and 2,

T_m – temperature of the mixture.

Mixing of substances with a different chemical composition:

$$\delta \dot{B} = T_a (MR) \left(\dot{n}_1 \sum_i z_{1i} \ln \frac{z_{1i}}{z_{mi}} + \dot{n}_2 \sum_i z_{2i} \ln \frac{z_{2i}}{z_{mi}} \right) \quad (C.29)$$

where:

$\dot{n}_1, \dot{n}_2$ – molar-fluxes of substances before mixing,

z_{1i}, z_{2i} – the molar-share of the „i-th” component before mixing,

z_{mi} – the molar-share of the „i-th” component after mixing.

Appendix D

Actual diagram and duration curve on the example of the demand and production of heat.

Physical quantities variable in time (random values), such as demand for heat or its production, are represented in the form of diagrams. Most often they concern periods of 24 hours or a whole year. As far as heat is concerned, they are constructed for the heating season.

The actual diagram of the demand for or production of heat provides information about the flux of heat in any given moment. The actual diagram may be subjected to algebraic operations (mostly addition or subtraction) on ordinates corresponding to the same moments of time. If the actual diagrams are repeatable it is expedient to apply average diagrams. Thus, for instance, average actual diagrams of the consumption of heat for preparing hot tap water are constructed separately for ordinary week-days, red-letter days and the days proceeding them. The averaging should not change the extreme values in the diagrams (e.g. maximum in the averaged diagram corresponds to the highest local maximum values in the individual diagrams).

Duration curves are constructed based on the representative test of actual diagrams arranging the ordinates according to diminishing values of the random value. Usually they concern longer periods of time (mostly one year). Figure D1 presents the construction of a duration curve based on an actual given diagram. In the actual diagram there are moments of time corresponding to concrete values of the random value. In contradiction to an actual diagram the duration curve provides information about the duration of the respective ranges of the random value. The point A on the duration curve informs us, for example, that during the time τ_A the heat flux is higher than $\dot{Q}_A$, and in the period $(8760 - \tau_A)$ the values are smaller than $\dot{Q}_A$. If the axis of abscissae is described by means of the relative time $\tau/8760$, then $\tau_A/8760$ denotes the probability of the occurrence of a heat load exceeding $\dot{Q}_A$.

Duration curves should not be subjected to algebraic operations (e.g. addition or subtraction of the ordinates) because they do not refer to the same moment of time. If the considered random values (e.g., two duration curves of the demand for heat) are independent of each other, the sum of or difference between both duration curves may be obtained by means of the convolution of individual diagrams (probabilistic addition or subtraction).

The duration curve may be described by several characteristic parameters, the physical interpretation of which is represented in Figure D2. The abscissa τ_o on the duration curve

denotes the operation of the consumer or producer of heat, whereas the difference $(8760 - \tau_o)$ presents idle time, planned or caused by damage.

The annual production or demand for heat Q_R is calculated by means of the relation:

$$Q_a = \int_0^{\tau_p} \dot{Q} d\tau \quad (D.1)$$

The annual time τ_p of the peak load is:

$$\tau_p = \frac{Q_a}{\dot{Q}_{\max}} \quad (D.2)$$

The mean value $\dot{Q}_m$ of the production or demand for heat:

$$\dot{Q}_m = \frac{Q_a}{\tau_o} \quad (D.3)$$

The degree of irregularity of the load m_o is defined as follows:

$$m_o = \frac{\dot{Q}_{\min}}{\dot{Q}_{\max}} \quad (D.4)$$

The degree of utilisation of the peak load is expressed by the relation:

$$m = \frac{\dot{Q}_m}{\dot{Q}_{\max}} = \frac{\tau_p}{\tau_o} \quad (D.5)$$

Among the characteristic quantities, the value τ_p is of great practical importance. For the given type of heat consumption, the values of τ_p fluctuate within narrow limits and may be determined based on statistical data. Knowing the mean value τ_p , the duration curves can be prognosticated.

The demand for heat required for heating, ventilation and air conditioning depends on the ambient temperature (further on called external temperature), which is a random value dependent on time. It is preset in the form of a duration curve based on meteorological observations gathered in the course of many years. Duration curves of the external temperature are constructed for the respective climatic zones. Figure D.4. presents a duration curve of the external temperature concerning one of the climatic zones in Poland.

If no exact duration curve for the given climatic zone is available, Raiss's reduced diagram may be applied (Fig. D.3.). This dependence is expressed by the relation:

$$\frac{T_b - T_{\text{ex}}}{T_b - T_{\text{ex min}}} = 1 - \sqrt[3]{\frac{\tau}{\tau_{hs}}} + \left(\frac{\tau}{\tau_{hs}}\right)^2 \left(1 - \sqrt{\frac{\tau}{\tau_{hs}}}\right) \quad (D.6)$$

where:

T_b - initial temperature at the beginning of the heating season,

T_{ex} - external temperature,

τ_{hs} - duration of the heating season.

This dependence is usually applied in approximative analyses.

The duration curve of the external temperature (e.g. Fig. D.4.) is used in calculations of the annual production of heat, electricity in CHP and the annual consumption of the chemical energy of fuels. Assuming the initial temperature at the beginning of the heating season is $+12^\circ\text{C}$, the duration of the heating season can be determined (e.g., $\tau_{hs} = 5400h$ in compliance with Fig. D.4.). Making use of the initial duration curve of the external temperature, the duration curve concerning the reduced random values $\dot{Q}_h / \dot{Q}_{h\max}$ or $(T_{in} - T_{ex}) / (T_{in} - T_{ex\min})$ can be constructed based on the characteristics of the demand for heat (Eq.5.1. in Chapter 5):

$$\frac{\dot{Q}_h}{\dot{Q}_{h\max}} = \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\min}} \quad (\text{D.7})$$

The annual demand for heat Q_a is expressed by the formula:

$$Q_a = \dot{Q}_{h\max} \int_0^{\tau_{hs}} \frac{\dot{Q}_h}{\dot{Q}_{h\max}} d\tau = \dot{Q}_{h\max} \int_0^{\tau_{hs}} \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\min}} d\tau \quad (\text{D.8})$$

The value of the integral in the last term is a characteristic quantity, constant for the given climatic zone. It expresses the annual duration τ_p in which the maximum (peak) heating is utilised power resulting from:

$$\tau_p = \int_0^{\tau_{hs}} \frac{T_{in} - T_{ex}}{T_{in} - T_{ex\min}} d\tau \quad (\text{D.9})$$

hence:

$$Q_a = \tau_p \dot{Q}_{h\max} \quad (\text{D.10})$$

The base for the construction of duration curves concerning the production of electricity in CHP and consumption of the chemical energy of fuels is the duration curve of the demand for heat.

If in the CHP plant a back-pressure turbine operates (Fig. 5.11 in Chapter 5), the electrical power is a function of the heating power and then the annual production of

electricity and annual consumption of the chemical energy of fuels E_{cha} are determined by means of the equations:

$$E_{ela} = \int_0^{\tau_{hs}} \dot{Q}_h \frac{\Delta h_s \eta_i \eta_{me}}{h_l - h_c - \eta_i \Delta h_s} (D.11)$$

$$E_{cha} = \int_0^{\tau_{hs}} \frac{\dot{Q}_h}{\eta_{Eb}} \frac{h_l - h_s}{h_l - h_s - \eta_i \Delta h_s} (D.12)$$

where:

Δh_s - isentropic enthalpy drop in turbine,

η_i - isentropic efficiency,

η_{me} - electromechanical efficiency,

h_l - specific enthalpy of live steam,

h_c - specific enthalpy of condensate,

η_{Eb} - energy efficiency of the boiler.

It should be stressed that the adiabatic and electromechanical efficiencies of the turbo-generator depend on the load.

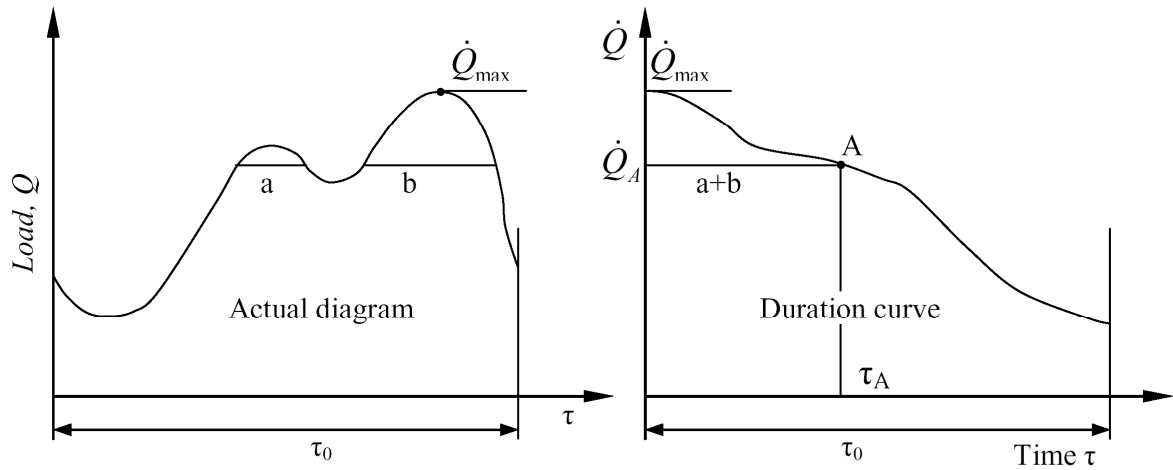


Fig. D1. Construction of duration curve on the base of actual diagram

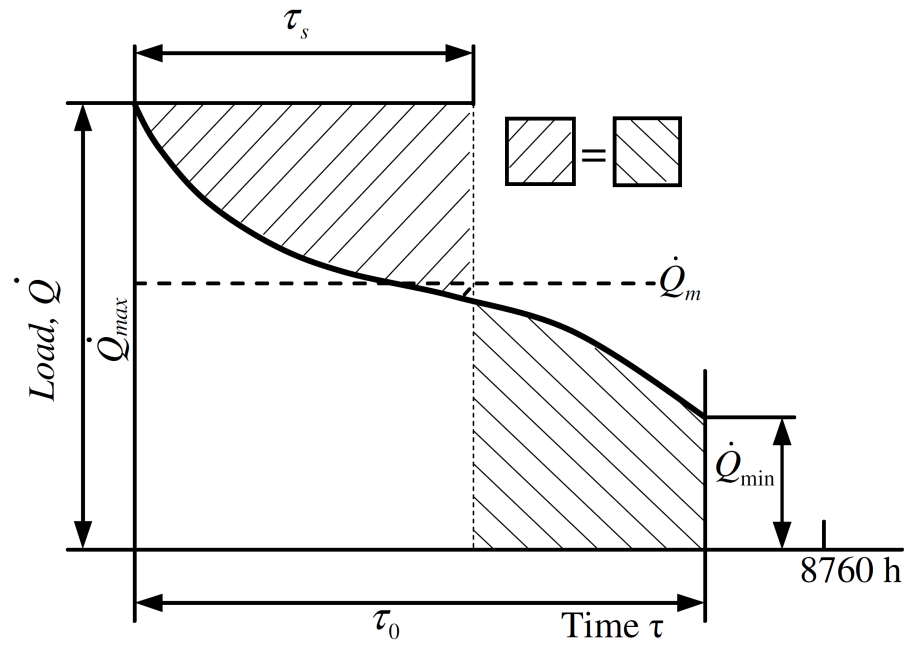


Fig. D2. Characteristics parameters of duration curve

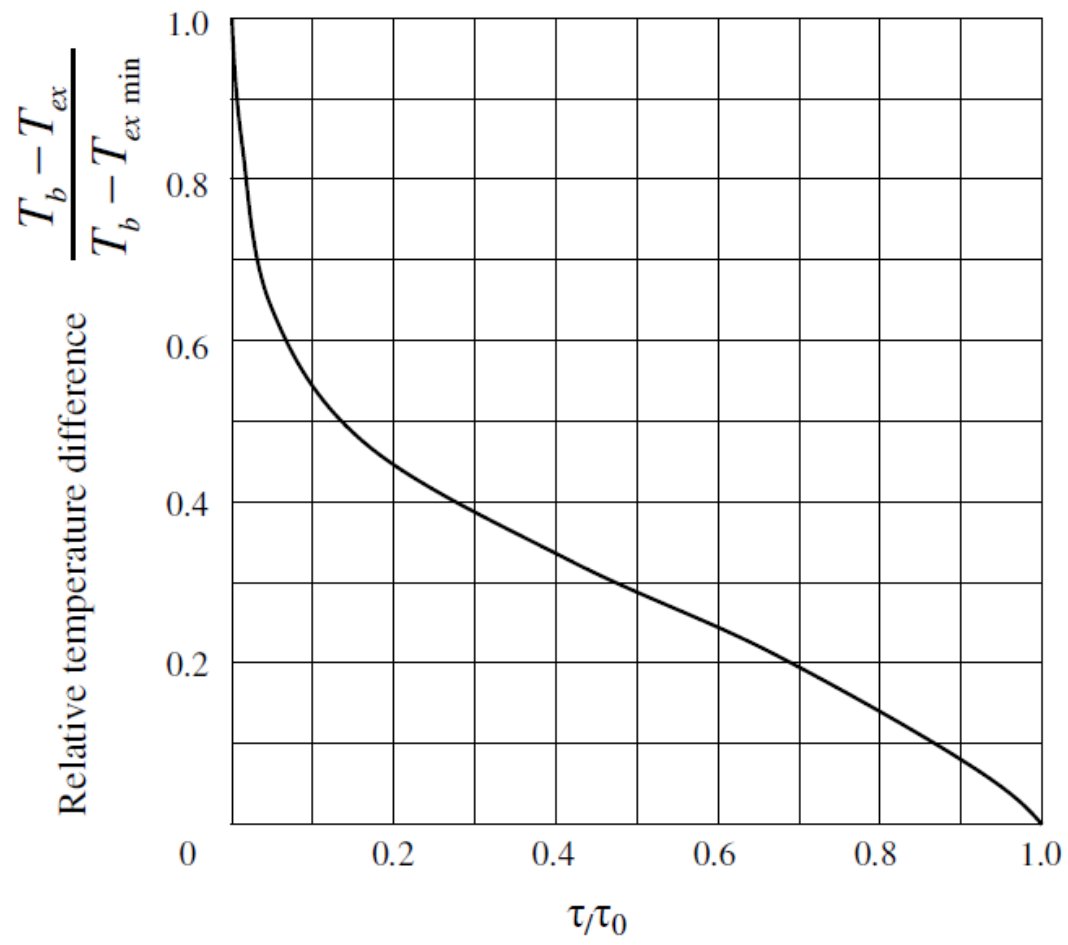


Fig. D3. Relative duration curve of external temperature

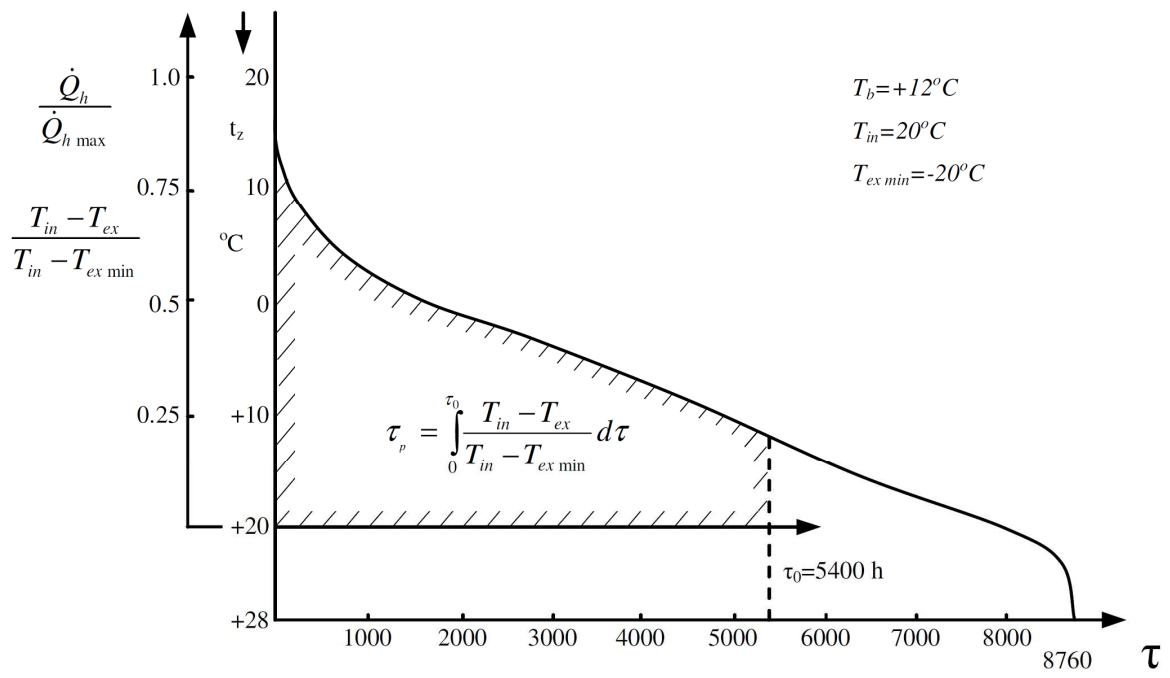


Fig. D.4. Application of the duration curve of external temperature to prepare the duration curve of heat demand

Appendix E

Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market- selected paragraphs and parts of annexes.

Introduction

The potential for use of cogeneration as a measure to save energy is underused in the Community at present. Promotion of high-efficiency cogeneration based on a useful heat demand is a Community priority given the potential benefits of cogeneration with regard to saving primary energy, avoiding network losses and reducing emissions, in particular of greenhouse gases. In addition efficient use of energy by cogeneration can also contribute positively to the security of energy supply and to the competitive situation of the European Union and its Member States. It is important because the EU is extremely dependent on its external energy supplies currently accounting for 50% of requirements and projected to rise to 70% by 2030 if current trends persists.

The increased use of cogeneration geared towards making primary energy savings could constitute an important part of the package of measures needed to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change, and of any policy package to meet further commitments.

Public support schemes for promoting cogeneration should focus mainly on support for cogeneration based on economically justified demand for heat and cooling. Economically justifiable demand shall mean the demand that does not exceed the needs for heat or cooling and which would otherwise be satisfied at market conditions by energy generation processes other than cogeneration.

The definition of “small scale cogeneration” comprises, *inter alia*, micro-cogeneration and distributed cogeneration units such as cogeneration units supplying isolated areas or limited residential, commercial or industrial demands.

“Micro-cogeneration unit” shall mean a cogeneration units with an installed capacity below 50 kW_e. “Small-scale cogeneration” shall mean cogeneration units with an installed capacity below 1 MW_e.

It is important that all forms of electricity produced from high-efficiency cogeneration (ANNEX III) can be covered by guarantees of origin. It is important to distinguish guarantees of origin clearly from exchangeable certificates.

Article 5 p.5 and p.6 (fragments):

5. A guarantee of origin shall:

- specify the lower calorific value of the fuel source from which the electricity was produced, specify the use of heat generated together with the electricity and finally specify the dates and places of production,
- specify the quantity of electricity from high-efficiency cogeneration in accordance with Annex II that the guarantee represents,
- specify the primary energy savings calculated in accordance with Annex III based on harmonised efficiency reference values established by the Commission as referred to in Article 4(1).

Member States may include additional information on the guarantee of origin.

6. Such guarantees of origin, issued according to paragraph 1, should be mutually recognized by the Member States, exclusively as proof of the elements referred in paragraph 5. Any refusal to recognize a guarantee of origin as such proof, in particular for reasons relating to the prevention of fraud, must be based on objective, transparent and non-discriminatory criteria.

In the event of refusal to recognize a guarantee of origin, the Commission may compel the refusing party to recognize it, particularly with regard to objective, transparent and non-discriminatory criteria on which such recognition is based.

ANNEX I

Cogeneration Technologies covered by this Directive

- (a) Combined cycle gas turbine with heat recovery
- (b) Steam backpressure turbine
- (c) Steam condensing extraction turbine
- (d) Gas turbine with heat recovery
- (e) Internal combustion engine
- (f) Microturbines
- (g) Stirling engines

- (h) Fuel cells
- (i) Steam engines
- (j) Organic Rankine cycles
- (k) Any other type of technology or combination thereof falling under the definition laid down in Article 3(a)

ANNEX II (fragments)

Calculation of electricity from cogeneration

Values used for calculation of electricity from cogeneration shall be determined on the basis of the expected or actual operation of the unit under normal conditions of use. For micro-cogeneration units the calculation may be based on certified values.

(a) Electricity production from cogeneration shall be considered equal to total annual electricity production of the unit measured at the outlet of the main generators;

(i) in cogeneration units of type (b), (d), (e), (f), (g) and (h) referred to in Annex I, with an annual overall efficiency set by Member States at a level of at least 75 %, and

(ii) in cogeneration units of type (a) and (c) referred to in Annex I with an annual overall efficiency set by Member States at a level of at least 80 %.

(b) In cogeneration units with an annual overall efficiency below the value referred to in paragraph (a)(i) (cogeneration units of type (b), (d), (e), (f), (g), and (h) referred to in Annex I) or with an annual overall efficiency below the value referred to in paragraph (a)(ii) (cogeneration units of type (a) and (c) referred to in Annex I) cogeneration is calculated according to the following formula:

$$E_{CHP} = H_{CHP} C \quad (E.1)$$

where:

E_{CHP} is the amount of electricity from cogeneration,

C is the power to heat ratio,

H_{CHP} is the amount of useful heat from cogeneration (calculated for this purpose as total heat production minus any heat produced in separate boilers or by live steam extraction from the steam generator before the turbine).

The calculation of electricity from cogeneration must be based on the actual power to heat ratio. If the actual power to heat ratio of a cogeneration unit is not known, the following

default values may be used, notably for statistical purposes, for units of type (a), (b), (c), (d), and (e) referred to in Annex I provided that the calculated cogeneration electricity is less or equal to total electricity production of the unit:

Type of the unit	Default power to heat ratio, C
Combined cycle gas turbine with heat recovery	0,95
Steam backpressure turbine	0,45
Steam condensing extraction turbine	0,45
Gas turbine with heat recovery	0,55
Internal combustion engine	0,75

If Member States introduce default values for power to heat ratio for units of type (f), (g), (h), (i), (j) and (k) referred to in Annex I, such default values shall be published and shall be notified to the Commission.

ANNEX III (fragments)

Methodology for determining the efficiency of the cogeneration process

Values used for calculation of efficiency of cogeneration and primary energy savings shall be determined on the basis of the expected or actual operation of the unit under normal conditions of use.

(a) High-efficiency cogeneration

For the purpose of this Directive high-efficiency cogeneration shall fulfil the following criteria:

- cogeneration production from cogeneration units shall provide primary energy savings calculated according to point (b) of at least 10 % compared with the references for separate production of heat and electricity,
- production from small scale and micro cogeneration units providing primary energy savings may qualify as high-efficiency cogeneration.

(b) Calculation of primary energy savings

The amount of primary energy savings provided by cogeneration production defined in accordance with Annex II shall be calculated on the basis of the following formula:

$$PES = \left(1 - \frac{1}{\frac{CHP H\eta}{Ref H\eta} + \frac{CHP E\eta}{Ref E\eta}} \right) \times 100\% \quad (E.2)$$

where:

PES is primary energy savings.

$CHP H\eta$ is the heat efficiency of the cogeneration production defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration.

$Ref H\eta$ is the efficiency reference value for separate heat production.

$CHP E\eta$ is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration. Where a cogeneration unit generates mechanical energy, the annual electricity from cogeneration may be increased by an additional element representing the amount of electricity which is equivalent to that of mechanical energy. This additional element will not create a right to issue guarantees of origin in accordance with Article 5.

$Ref E\eta$ is the efficiency reference value for separate electricity production.

Appendix F

Calculus of the cumulative consumption of energy

Direct consumption of energy does not comprise all the energy required to produce some given useful product, because the applied raw materials, semi-products and energy carriers also require energy for the purpose of:

- extracting non-renewable primary energy and raw materials,
- producing materials and semi-products,
- processing primary energy into final energy carriers,
- transporting raw materials, semi-products, materials and energy carriers,
- constructing production plants and installations in which the given product is manufactured.

Figure F1 explains the idea of the calculus of the cumulative consumption of energy.

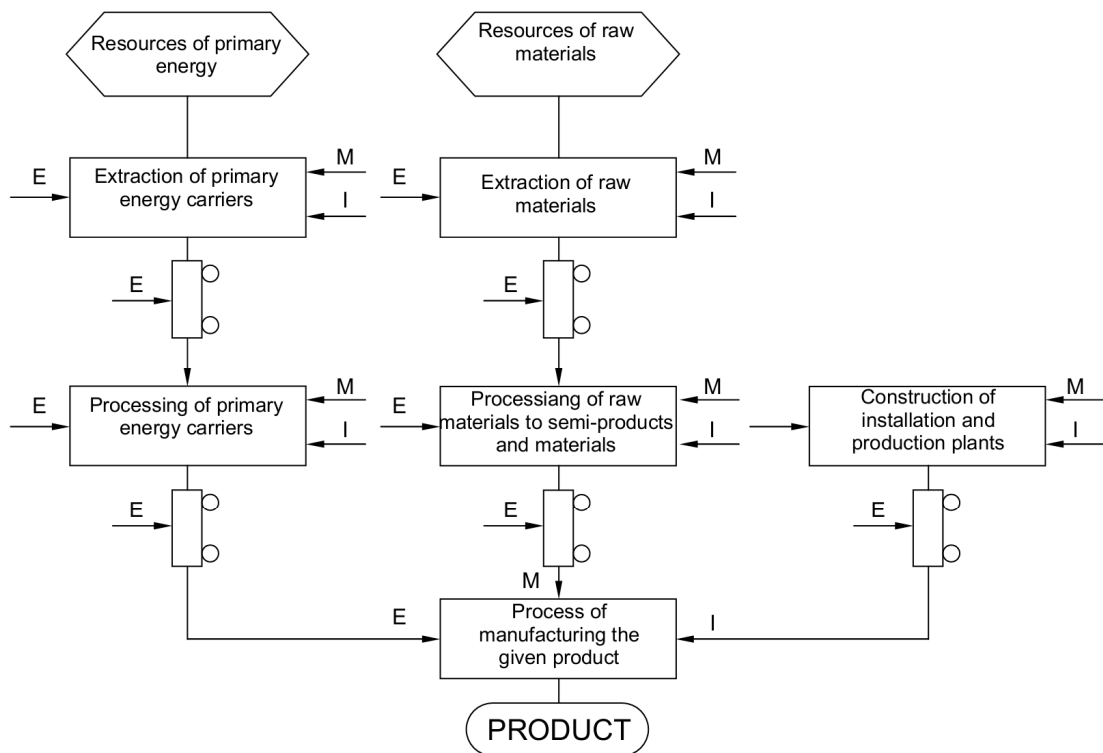


Fig.F1 Idea of the calculus of the cumulative consumption of energy; E- energy, M- materials, I- installations (Adapted from Bibrowski (ed.) - Cumulative energy consumption (in Polish). PWN, Warsaw 1983)

The index e_{kj}^* of cumulative consumption of the k-th form of energy per unit of the j-th product may be defined by the following formula:

$$e_{kj}^* = \frac{E_{kj}}{G_{Nj}} = \frac{\Delta E_k}{\Delta k_j} \quad (\text{F.1})$$

where:

E_{kj} - total consumption of the k-th form of energy in the network of manufacturing and transporting processes connected with the manufacturing of the j-th product in the considered period of time (e.g., in the course of one year),

G_{Nj} - net-production of the j-th product,

ΔE_k - increased consumption of the k-th form of energy all over the country due to the increased final production of the j-th product,

Δk_j - increased final production of the j-th product.

The quantity E_{kj} comprises:

- direct consumption of the k-th form of energy,
- consumption of the k-th form of energy for gaining and processing the k-th form of energy (own consumption),
- consumption of the k-th form of energy for transporting,
- consumption of the k-th form of energy for the extraction of raw materials and production of materials for manufacturing the given j-th product,
- consumption of the k-th form of energy for transporting these raw materials and materials from the place of their extraction to the place of their consumption,
- consumption of the k-th form of energy for the production of installations and production plants, in which the given j-th product is manufactured.

Practically, the cumulative consumption of primary energy is applied in systems analysis:

$$e_j^* = \sum_p e_{pj}^* \quad (\text{F.2})$$

where:

e_j^* - index of cumulative consumption of primary energy per unit of the j-th product,

e_{pj}^* - index of cumulative consumption of the p-th kind of primary energy

p - running number of primary energy.

The following ways of applying the calculus of cumulative consumption of energy might be suggested:

- planning the required increase of the production of fuels and energy indispensable for the predicted increase of the production of some given product,
- comparison of total energy expenditures concerning various techniques applied in manufacturing some given product (e.g. steel or cement),
- evolution of total energy expenditure for the purpose of producing useful energy,
- comparison of cumulative energy consumption burdening the GDP attained in various branches of the domestic economy,
- assessment of possibilities of saving energy with an adequate choice of technology,
- assessment of the effect of substituting energy carriers and materials on the consumption of primary energy,
- assessment of the effect of changes in the price of energy carriers on the costs of manufacturing a given product.

The cumulative energy efficiency η_E^* is calculated according to the principle of the method of cumulative energy consumption:

$$\eta_E^* = \frac{E_u}{\sum_j G_j e_j^*} \quad (\text{F.3})$$

where:

E_u - useful energy,

G_j - consumption of the j-th energy carrier or material,

e_j^* - index of cumulative energy consumption burdening the j-th energy carrier or material.

The index of cumulative energy consumption is calculated as the reciprocal of cumulative energy efficiency:

$$e^* = \frac{1}{\eta_E^*} \quad (\text{F.4})$$

The calculus of cumulative energy consumption of primary energy concerns, of course, non-renewable energy resources. The indices of cumulative primary energy consumption are determined, first of all, on the level of the economy of the whole country. The most effective and accurate method of calculating the mean indices concerning the country is the “input-output” method of the balances of cumulative energy consumption. The condition of its application is a closed balance of all branches of the economy of the country

in compliance with Leontief’s “input-output economics”. Also the method of analysing the processes (sequence method) may be applied. This latter method consists in the analysis of processes analysed backwards from the level of the given product to those links of the network of interconnections when the addition of any successive link leads to a negligibly small increase of the value of the index of cumulative energy consumption. Figure F2 presents the set of graphical symbols applied in the sequence method.

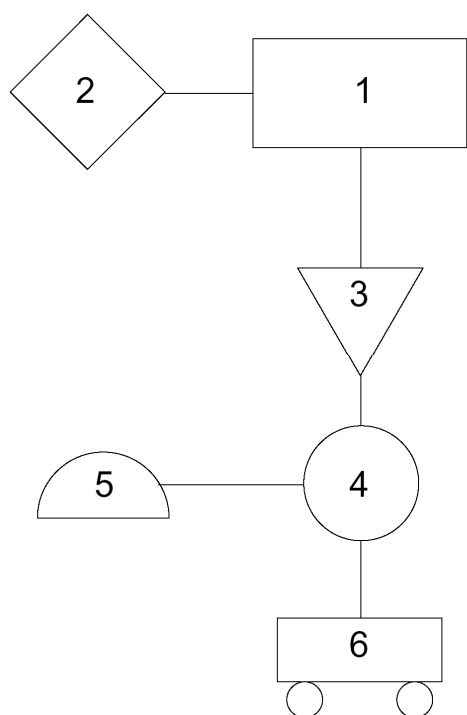


Fig. F2. Graphical symbols applied in the sequence method; 1 - name of process, 2 - consumption of energy for constructing the production plants and installations, 3 - energy consumption in the process, 4 - name of the product, 5 - consumption of primary energy, 6 - consumption of energy for transport.

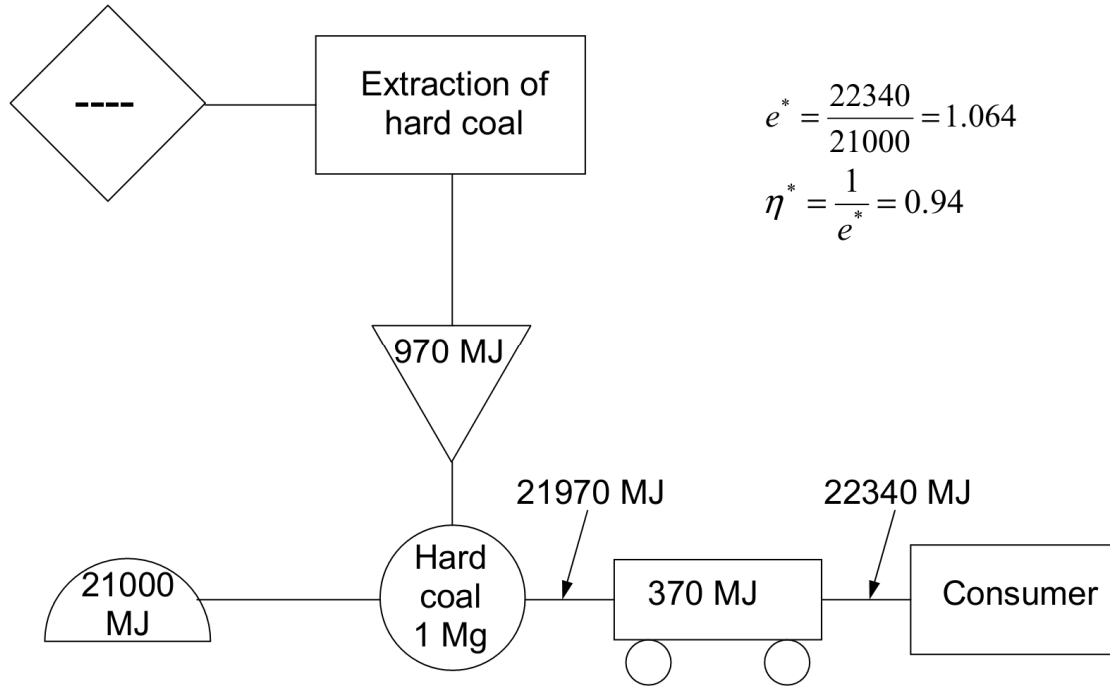


Fig.F3. Scheme for calculating the index of cumulative energy consumption of hard coal

The sequence method has been applied to calculate the index of cumulative energy consumption concerning the extraction of hard coal, calculated loco consumer (Fig.F3). The investment component has been left out of account as being negligible when compared with the chemical energy of coal. In the case of electricity, if the investment component is also not taken into account the cumulated energy efficiency, calculated loco consumer, is presented by the relation:

$$\eta_{Eel}^* = \eta_{ex}^* \eta_{EelN} \eta_{tr} \quad (F.5)$$

where:

η_{Eel}^* - cumulated energy efficiency of the extraction and transport of fuels (in the case of hard coal - $\eta_{ex}^* = 0,94$),

η_{EelN} - net energy efficiency of the production of electricity (e.g. $\eta_{EelN} = 0,36$ - subcritical power station fired with hard coal),

η_{tr} - efficiency of electricity transmission (e.g. $\eta_{tr} = 0,89$).

Similarly, the cumulative energy efficiency of gaining heat from the heating plant, calculated loco consumer, results from the relation:

$$\eta_{Eh}^* = \eta_{ex}^* \eta_{Ehp}^* \eta_{th}^* \quad (F.6)$$

where:

η_{Ehp} - energy efficiency of a heating plant fired with hard coal (e.g.),

η_{th} - energy efficiency of transporting the heat (e.g.).

Substituting these values in Eq.F6 we have:

$$\eta_{Eh}^* = 0,64$$

Figure F4 presents the scheme for calculating the index of cumulative energy consumption concerning lime burning. It has been assumed that the indices of cumulative energy consumption concerning coke, electricity and limestone are mean values all over the country. This assumption means that the influence of the process of lime burning does not greatly influence the entire energy management of the country.

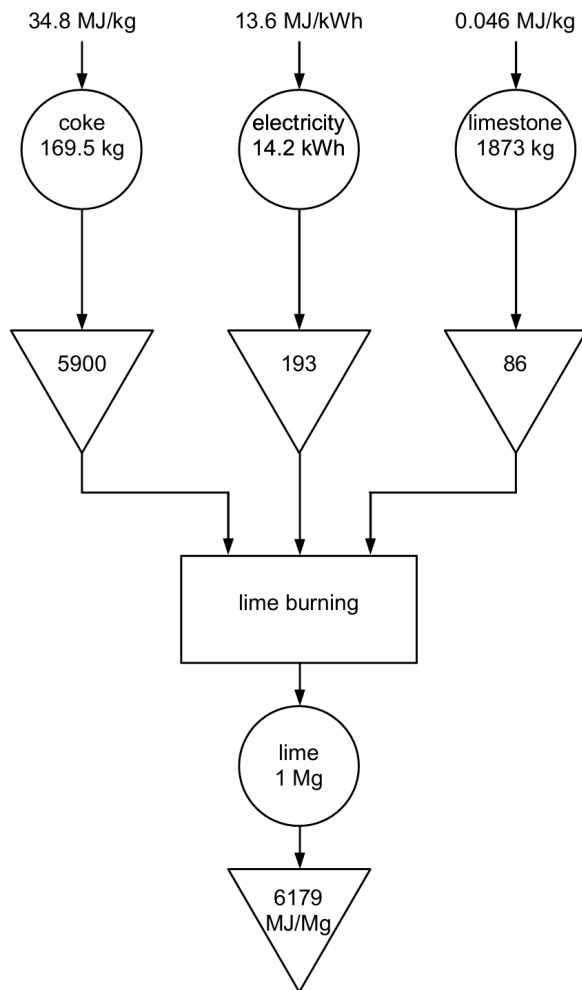


Fig. F4. Scheme for calculating the index of cumulative energy consumption concerning lime burning

Table F1 quotes exemplary values of the indices of cumulative energy consumption and cumulated energy efficiency concerning selected fuels and final energy carriers.

Tab. F.1. Indices of cumulative energy consumption and cumulated energy efficiency

Energy carrier	e^* J/J	η_E^*
Hard coal	1,064	0,940
Lignite	1,083	0,923
Coke	1,310	0,763
Fuel oil	1,168	0,856
Petrol	1,238	0,808
Natural gas	1,020	0,980
Electricity (loco power station)	3,36	0,298
Electricity (loco consumer)	3,83	0,261
Heat (heating plant)	1,57	0,637
Heat (CHP)	1,23	0,813