MULTI-OBJECTIVE DESIGN AND OPTIMIZATION OF DISTRICT ENERGY SYSTEMS INCLUDING POLYGENERATION ENERGY CONVERSION TECHNOLOGIES

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PAR

Céline Isabelle WEBER

ingénieure en gestion d'entreprise et production diplômée EPF
de nationalité suisse et originaire de Menzingen (ZG)

acceptée sur proposition du jury:

Prof. J. R. Thome, président du jury
Prof. D. Favrat, Dr F. Maréchal, directeurs de thèse
Prof. T. Fransson, rapporteur
Dr O. Ouzilou, rapporteur
Prof. H. B. Püttgen, rapporteur

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Abstract

In the present context of finding ways to decrease CO_2 emissions linked with human activity, district energy systems including polygeneration energy conversion technologies are likely to play a major role. District energy systems meet the heating, hot water, cooling and electricity requirements of a district. Because they meet several types of energy requirements, and for more than one single building, district energy systems represent good opportunities to implement polygeneration energy conversion technologies. Polygeneration energy conversion technologies indeed provide different energy services simultaneously, helping to decrease the CO_2 intensity compared to energy conversion technologies that meet only one energy service. Moreover, when providing energy to a whole district, polygeneration energy conversion technologies can take advantage of the various load profiles of the buildings by compensating the fluctuations and having therefore a smoother operation.

A district energy system comprises essentially two parts: the plant with the polygeneration energy conversion technologies, and the distribution networks (heating and cooling). When designing the energy system for a district, one has therefore to define which type of polygeneration energy conversion technologies are best suited for the district, as well as which building are worse connecting to the system and which buildings shouldn't be connected (for instance if they are located too far away from the other buildings or if they have too small requirements to justify a connection from the plant). Moreover the operation strategy needs to be defined.

In the present thesis, a method is developed that helps designing and optimizing district energy systems, from the structuring of the information available for the district (energy consumption profiles, location of the buildings, available energy sources, possible layouts for the pipes,...), over the thermo-economic modelling of the energy conversion technologies, the design of the network and the simulation of its operation strategy, and finally the evaluation of the results in terms of CO_2 emissions and costs. The design and optimization of the district energy system is a multi-objective Mixed Integer Non Linear Programming problem. To solve this problem, a decomposition strategy including a master and a slave problem was developed. The master optimization problem takes care of the energy conversion technologies, whereas the slave optimization problem optimizes the network part. The two sub-problems are solved iteratively and result in the definition of a Pareto optimal curve that gives the trade-offs between the emissions and the costs for various configurations satisfying the requirements of the district. A configuration is characterized by given types and sizes of energy conversion technologies, their location in the district, the network layout, as well as the operation strategy of the technologies. Due to the time dependent energy consumption profiles and the geographical location of the buildings and plant, the method developed combines two well known types of problems, namely the multi-period optimization problems and the network problems.

The method developed allows to take into account various constraints such as limited availability of energy sources, forbidden connections between buildings (for instance if a large river separates these two buildings), or else space limitations in underground technical channels. The capabilities of the method are demonstrated by means of a test case, as well as a real case in the Canton of Geneva. The results show the importance of considering all the energy services together (and not separately). Energy systems including a gas engine or a gas turbine combined cycle, together with heat pumps, indeed help decreasing both the emissions and the costs compared to the actual configurations. In the Geneva case study for instance, emissions can be decreased by up to 45%, with a simultaneous costs reduction of 24%. However, the method only deals with water networks, while in some cases space limitations and safety issues make the use of water impossible. A new type of district energy system based on CO_2 as energy transfer medium (instead of water), is therefore developed in order to take such issues into account. This new system, that led to the submission of a patent, meets all the different types of energy requirements with only two pipes (instead of three or four like in conventional water based system), and uses the latent heat of CO_2 as driving force, instead of the specific heat.

Keywords: District energy systems, Mixed Integer Non Linear Programming, Branch-and-bound, Evolutionary algorithm, Thermo-economic modelling, CO_2 mitigation, CO_2 based energy system

Résumé

Dans le contexte actuel de réduction des émissions de CO_2, les systèmes urbains sont appelés à jouer un rôle important. Les systèmes urbains satisfont les demandes de chauffage, eau chaude sanitaire, climatisation et électricité de quartiers entiers. Dû au fait qu'ils satisfont plusieurs besoins (et pas seulement le chauffage par exemple), pour plusieurs bâtiments, les systèmes urbains représentent des opportunités idéales pour l'installation de technologies de conversion d'énergie avec polygénération. Les technologies avec polygénération fournissent plusieurs types d'énergie simultanément et réduisent ainsi les densité de CO_2 émises. D'autre part, utilisées dans des systèmes urbains, ces technologies peuvent mettre à profit les différents profils de consommation de chacun des bâtiments en compensant les fluctuations et ainsi être opérées à des régimes relativement constants.

Un système urbain est composé essentiellement de deux parties: les technologies et les réseaux de distribution (chaud et froid). Pour concevoir un système urbain il faut donc déterminer le type et la taille des technologies qui vont être utilisées ainsi que la configuration des réseaux (en tenant compte du fait que certains bâtiments trop éloignés du reste du quartier, ou ayant des profils de consommations trop faibles, auraient avantage à ne pas être connectés et à avoir leur propre système). D'autre part il faut définir le régime de fonctionnement des installations.

Une méthode a été développée afin de configurer et optimiser des systèmes urbains. Cette méthode comprend une phase de structuration de l'information disponible pour le quartier (profils de consommation, emplacement des bâtiments, sources énergétiques disponibles, tracés de conduites autorisés,...), des modèles thermo-économiques pour les technologies de conversion d'énergie, la configuration des réseaux et le régime de fonctionnement des installations, et enfin l'évaluation des résultats obtenus en termes d'émissions et de coûts. La configuration et l'optimisation de systèmes urbains est un problèmes multi-objectif, non linéaire, en nombres entiers. Pour résoudre ce problème une stratégie de décomposition a été développée afin de séparer le problème en un sous-problème maître et un sous-problème esclave. Ces deux sous-problèmes sont résolus de manière itérative, et le résultat est donné sous forme d'une courbe de Pareto comprenant différentes configurations, avec leurs émissions et leurs coûts. Une configuration est caractérisée par des types et tailles de technologies donnés, leur emplacement dans le quartier, la configuration des réseaux, ainsi que le mode opératoire des technologies. Dû à son aspect temporel (profils de consommation) et spatial (emplacement des bâtiments et technologies), ce problème de configuration et optimisation de systèmes urbains combine deux types de problèmes bien connus: les problèmes multi-périodes et les problèmes de réseaux.

La méthode développée permet de tenir compte de différentes contraintes telles que la disponibilité limitée de certaines ressources énergétiques, les tracés de conduites interdits entre deux bâtiments (par exemple si un large fleuve sépare les deux bâtiments), ou encore la place limitée pour les conduites dans des galeries techniques par exemple. La méthode est démontrée à l'aide d'un cas d'étude ainsi que d'un cas réel dans le canton de Genève. Les résultats démontrent l'importance de considérer tous les services énergétiques simultanément (et non individuellement). Des systèmes énergétiques comprenant des pompes à chaleur combinées à un moteur à gaz ou à un cycle combiné (turbine à gaz et turbine à vapeur), permettent en effet de diminuer non seulement les émissions de CO_2, mais également les coûts (par rapport aux systèmes actuels). Dans le cas de Genève par exemple, les émissions peuvent être réduites de 45% tout en diminuant les coûts de 24%. Cependant, la méthode développée ne permet de considérer que des réseaux de distribution utilisant de l'eau comme fluide de travail, alors même que dans certains cas l'eau n'est pas opportune, soit pour des raisons de limitation de la place disponible, soit pour des raisons de sécurité. Un tout nouveau type de systèmes urbains utilisant le CO_2 comme fluide caloporteur à la place de l'eau a donc été développé afin de tenir compte de ces facteurs. Ce nouveau système, qui a abouti à une demande de dépôt de brevet, permet de répondre aux différents besoins énergétiques à l'aide de conduites seulement (en lieu et place des quatre ou trois conduites habituellement requises), et se sert de la chaleur latente du CO_2 plutôt que de la chaleur spécifique.

Mots clés: Systèmes énergétiques urbains, problème de programmation non linéaire en nombres entiers, branch-and-bound, algorithme évolutif, modélisation thermo-économique , émissions de CO_2, système énergétique basé sur le CO_2

Contents

Symbols

Roman letters

$A_{\mathrm{cs},i,j}$	Surface area of the pipe between nodes i and j in the supply cooling network [m^2]
$A_{\mathrm{hs},i,j}$	Surface area of the pipe between nodes i and j in the supply heating network [m^2]
$A_{\mathrm{cs},k}^{HEX}$	Area of the heat exchanger between the cooling network and the building at node k [m^2]
$A_{\mathrm{hs},k}^{HEX}$	Area of the heat exchanger between the heating network and the building at node k [m^2]
An^{aw}	Annuity factor for the individual back-up air/water heat pump(s) [-]
An^{boiler}	Annuity factor for the individual back-up boiler(s) [-]
An^{chiller}	Annuity factor for the individual back-up chiller(s) [-]
An^{HEX}	Annuity factor for heat exchanger(s) [-]
An^{i}	Annuity factor of any device i [-]
An^{pipe}	Annuity factor for the pipes [-]
An^{pump}	Annuity factor for the circulation pump(s) [-]
An^{ww}	Annuity factor for the individual back-up water/water heat pump(s) [-]
b^{grid}	Price paid by the grid when buying electricity from the district energy conversion technologies [CHF/kWh]
C	Investment cost of a device (in general) [CHF]
C^{aw}	Total annual investment costs for individual back-up air/water heat pump(s) including amortisation and maintenance [CHF/year]
C_{fix}^{aw}	Fixed cost for individual back-up air/water heat pump(s) [CHF]
c_{prop}^{aw}	Proportional cost for individual back-up air/water heat pump(s) [CHF/kWth]
C^{boiler}	Total annual investment costs for individual back-up boilers including amortisation and maintenance [CHF/year]
$C_{fix}^{\mathrm{boiler}}$	Fixed cost for individual back-up boilers(s) [CHF]

$c^{\mathrm{boiler}}_{prop}$	Proportional cost for individual back-up for boilers(s) [CHF/kWth]
C^{CE}	Investment cost for the civil engineering and auxiliary equipment for a combined cycle [CHF]
C^{chiller}	Total annual investment costs for individual back-up chiller(s) including amortisation and maintenance [CHF/year]
$C^{\mathrm{chiller}}_{fix}$	Fixed cost for individual back-up chillers(s) [CHF]
$c^{\mathrm{chiller}}_{prop}$	Proportional cost for individual back-up chillers(s) [CHF/kWth]
$C^{\mathrm{CO_2}}$	Total annual penalties for $\mathrm{CO_2}$ emissions [CHF/year]
c^{gas}	Specific gas cost [CHF/kWh]
C^{gas}	Total annual costs for natural gas [CHF/year]
c^{GE}	Specific investment cost for a gas engine [CHF/kWel]
C^{GE}	Investment cost for a gas engine [CHF]
C^{GT}	Investment cost for the gas turbine belonging to the combined cycle [CHF]
c^{grid}	Specific grid cost [CHF/kWh]
C^{grid}	Total annual costs for the electricity from the grid [CHF/year]
C^{hex}	Total annual investment costs for the heat exchangers including amortisation and maintenance [CHF/year]
$C^{\mathrm{HEX\_inv}}_{\mathrm{cs},k}$	Investment costs for the heat exchanger between the building at node k and the cooling network [CHF]
$C^{\mathrm{HEX\_inv}}_{\mathrm{hs},k}$	Investment costs for the heat exchanger between the building at node k and the heating network [CHF]
c^{HP}	Specific investment cost for a district heat pump [CHF/kWth]
C^{HP}	Investment cost for a district heat pump [CHF]
c^{oil}	Specific heating oil cost [CHF/kWh]
C^{oil}	Total annual costs for heating oil [CHF/year]
$C^{\mathrm{pipe}}_{\mathrm{cs}}$	Total annual investment costs for the pipes of the cooling network including amortisation and maintenance [CHF/year]
$C^{\mathrm{pipe}}_{\mathrm{hs}}$	Total annual investment costs for the pipes of the heating network including amortisation and maintenance [CHF/year]
C^{pipe}_{fix}	Fixed cost for the pipes (supply and return) [CHF]
c^{pipe}_{prop}	Proportional cost for the pipes (supply and return) [CHF/($\mathrm{m}^2\cdot$ m)]
C^{pump}	Total annual investment costs for the circulation pump(s) including amortisation and maintenance [CHF/year]
C^{ref}	Investment cost for a device taken as reference (in general) [CHF]
C^{ST}	Investment cost for the steam turbine belonging to the combined cycle [CHF]
C^{ww}	Total annual investment costs for individual back-up water/water heat pump(s) including amortisation and maintenance [CHF/year]

C_{fix}^{ww}	Fixed cost for water/water heat pump(s) [CHF]
c_{prop}^{ww}	Proportional costs for water/water heat pump(s) [CHF/kWth]
${co_2}^{\mathrm{gas}}$	Specific CO_2 emissions for natural gas [kg-CO_2/kWh]
${co_2}^{\mathrm{grid}}$	Specific CO_2 emissions for electricity from the grid [kg-CO_2/kWh]
${co_2}^{\mathrm{oil}}$	Specific CO_2 emissions for heating oil [kg-CO_2/kWh]
$COP_{t,k}^{\mathrm{aw}}$	Coefficient of performance of the individual back-up air/water heat pump at node k during period t [-]
$COP_{t,k}^{\mathrm{chiller}}$	Coefficient of performance of the individual back-up chiller at node k during period t [-]
$COP_{t,k}^{\mathrm{ww}}$	Coefficient of performance of the individual back-up water/water heat pump at node k during period t [-]
cp_{Exhst}^{GT}	Specific isobaric heat of the exhaust gas from the gas turbine [kJ/(kg·K)]
$cp_{H_2O}^{\mathrm{liq}}$	Specific isobaric heat of water [kJ/(kg·K)]
$cp_{H_2O}^{\mathrm{vap}}$	Specific isobaric heat of steam [kJ/(kg·K)]
D_t	Duration of period t [h/year]
$Dist_{i,j}$	Distance between nodes i and j [m]
$\dot{E}_{t,k}^{\mathrm{aw}}$	Average hourly electricity rate required by the individual back-up air/water heat pump at node k during period t [kW]
$\dot{E}_{t,k}^{\mathrm{chiller}}$	Average hourly electricity rate required by the individual back-up chiller at node k during period t [kW]
$\dot{E}_{t,k}^{\mathrm{cons}}$	Average hourly electricity rate required by the building at node k during period t [kW]
$\dot{E}_{ht,t}^{\mathrm{exp}}$	Average hourly electricity rate exported to the grid during period t by device ht [kW]
$\dot{E}_{t}^{\mathrm{grid}}$	Average hourly electricity rate bought from the grid during period t [kW]
$\dot{E}_{t}^{\mathrm{loss}}$	Average hourly electricity rate losses during period t [kW]
$\dot{E}_{t}^{\mathrm{pump}}$	Total pumping power for the cooling and heating networks during period t [kW]
$\dot{E}_{t}^{\mathrm{sold}}$	Average hourly electricity rate sold during period t [kW]
$\dot{E}_{ht,t,k}^{\mathrm{tech}}$	Average hourly electricity rate produced or required during period t at node k by device ht [kW]
$\dot{E}_{t,k}^{\mathrm{ww}}$	Average hourly electricity rate required by the individual back-up water/water heat pump during period t at node k [kW]
Ex_H	Yearly exergy requirements for heating [kJ/year]
$\dot{E}x_{H,t,k}$	Average hourly heating exergy rate requirements [kW]
$\dot{E}x_{\mathrm{q}}$	Exergy rate of the energy rate $\dot{Q}$ [kW]
Fm^{aw}	Maintenance factor for individual back-up air/water heat pump(s) [-]

Fm^{boiler}	Maintenance factor for individual back-up boiler(s) [-]
Fm^{chiller}	Maintenance factor for individual back-up chillers(s) [-]
Fm^{HEX}	Maintenance factor for heat exchanger(s) [-]
Fm^{pipe}	Maintenance factor for the pipes [-]
Fm^{pump}	Maintenance factor for the circulation pump(s) [-]
Fm^{ww}	Maintenance factor for individual back-up water/water heat pump(s) [-]
$\hat{h}_{air}$	Surenthalpy of air at the outlet of the compressor [kJ/kg]
$\hat{h}_{fuel}$	Surenthalpy of fuel at 30°C [kJ/kg]
h_{H_2O}	Enthalpy of water/steam in the heat recovery steam generator [kJ/kg]
$\Delta h_{H_2O}^{\text{evap,cp}}$	Latent heat of water at the condensing pressure in the heat exchanger after the steam turbine [kJ/kg]
$\Delta h_{H_2O}^{\text{evap,hp}}$	Latent heat of water at the higher pressure level of the steam turbine [kJ/kg]
$\Delta h_{H_2O}^{\text{evap,lp}}$	Latent heat of water at the lower pressure level of the steam turbine [kJ/kg]
$\Delta h_{fuel}^{\text{lhv}}$	Lower heating value of fuel [kJ/kg]
I^{el}	Total annual income from the selling of electricity [CHF/year]
K	Heat transfer coefficient [kW/m]
L	Length of the pipe [m]
$\boldsymbol{M}$	Arbitrarily chosen big value [-]
$\dot{M}$	Mass flow rate (in general) [kg/s]
$\dot{M}_{air}$	Mass flow rate of air [kg/s]
$\dot{M}_{\text{cr},t,i,j}$	Mass flow rate of water flowing during period t from node i to j in the cooling return network [kg/s]
$\dot{M}_{\text{cs},t,i,j}$	Mass flow rate of water flowing during period t from node i to j in the cooling supply network [kg/s]
$\dot{M}_{\text{hr},t,i,j}$	Mass flow rate of water flowing during period t from node i to j in the heating return network [kg/s]
$\dot{M}_{\text{hs},t,i,j}$	Mass flow rate of water flowing during period t from node i to j in the heating supply network [kg/s]
$\dot{M}_{fuel}$	Fuel mass flow rate [kg/s]
$\dot{M}_{\text{cn},t,k}^{\text{build}}$	Mass flow rate of water from the cooling network flowing during period t through the heat exchanger between the building at node k and the network [kg/s]
$\dot{M}_{\text{hn},t,k}^{\text{build}}$	Mass flow rate of water from the heating network flowing during period t through the heat exchanger between the building at node k and the network (for heating *and* hot water purposes) [kg/s]

$\dot{M}^{\mathrm{GT}}_{Exhst}$	Mass flow rate of the exhaust gas from the gas turbine at part load [kg/s]
$\dot{M}^{\mathrm{GT}^0}_{Exhst}$	Mass flow rate of the exhaust gas from the gas turbine at nominal load [kg/s]
$\dot{M}^{\mathrm{hn\_ww}}_{\mathrm{hn},t,k}$	Mass flow rate of water from the heating network flowing during period t through the heat exchanger between the individual back-up water/water heat pump implemented in the building at node k and the network [kg/s]
$\dot{M}^{\mathrm{hp}}_{H_2O}$	Mass flow rate of steam flowing through the high pressure steam turbine [kg/s]
$\dot{M}^{\mathrm{lp}}_{H_2O}$	Mass flow rate of steam flowing through the low pressure steam turbine [kg/s]
$\dot{M}^{\mathrm{tech}}_{\mathrm{cn},t,k}$	Mass flow rate of water from the cooling network flowing during period t through the heat exchanger between the district energy conversion technologies at node k, and the cooling network [kg/s]
$\dot{M}^{\mathrm{tech}}_{\mathrm{hn},t,k}$	Mass flow rate of water from the heating network flowing during period t through the heat exchanger between the district energy conversion technologies at node k, and the heating network [kg/s]
$\dot{M}^{\mathrm{ub}}_{\mathrm{cs}}$	Maximum mass flow rate of water that can potentially flow in the cooling supply network cs between any two nodes, all periods included [kg/s]
$\dot{M}^{\mathrm{ub}}_{\mathrm{hs}}$	Maximum mass flow rate of water that can potentially flow in the heating supply network hs [kg/s] between any two nodes, all periods included [kg/s]
Ms^{aw}	Marshall-Swift factor for the desired accounting year for individual back-up air/water heat pump(s) [-]
Ms^{boiler}	Marshall-Swift factor for the desired accounting year for individual back-up boiler(s) [-]
Ms^{chiller}	Marshall-Swift factor for the desired accounting year for individual back-up chiller(s) [-]
Ms^{HEX}	Marshall-Swift factor for the desired accounting year for heat exchanger(s) [-]
Ms^{pipe}	Marshall-Swift factor for the desired accounting year for the pipes [-]
Ms^{pump}	Marshall-Swift factor for the desired accounting year for the circulation pump(s) [-]
Ms^{ww}	Marshall-Swift factor for the desired accounting year for individual back-up water/water heat pump(s) [-]
N^i	Lifetime of a device i (in general) [year]
p^{drop}_t	Specific pressure losses for a 1 meter long pipe during period t [Pa/m]
$\dot{Q}$	Energy rate [kW]

$\dot{q}^{\mathrm{loss}}_{t}$	Average hourly specific heat losses for a 1 meter long pipe during period t [kW/m]
$\dot{Q}_{\mathrm{cs},t,i,j}$	Hourly energy stream between nodes i and j in the cooling supply network during period t [kW]
$\dot{Q}_{\mathrm{hs},t,i,j}$	Hourly energy stream between nodes i and j in the heating supply network during period t [kW]
$\dot{Q}^{\mathrm{aw}}_{t,k}$	Hourly heat rate provided by the individual back-up heat pump during period t at node k for the heating and hot water requirements [kW]
$\dot{Q}^{\mathrm{boiler}}_{t,k}$	Hourly heat rate provided by the individual back-up boiler during period t at node k for the heating and hot water requirements [kW]
$\dot{Q}^{\mathrm{build}}_{\mathrm{cs},t,k}$	Hourly cooling rate provided by the cooling supply network during period t at node k [kW]
$\dot{Q}^{\mathrm{build}}_{\mathrm{hs},t,k}$	Hourly heat rate delivered by the heating supply network for heating and hot water requirements during period t to the building at node k [kW]
$\dot{Q}^{\mathrm{CC}}_{\mathrm{hs}}$	Hourly heat rate provided by the combined cycle to the heating network [kJ/kg]
$\dot{Q}^{\mathrm{chiller}}_{t,k}$	Hourly cooling rate provided by the individual back-up chiller during period t at node k for the cooling requirements [kW]
$\dot{Q}^{\mathrm{cons}}_{C,t,k}$	Average hourly cooling rate requirements during period t at node k [kW]
$\dot{Q}^{\mathrm{cons}}_{H,t,k}$	Average hourly heat rate requirements during period t at node k [kW]
$\dot{Q}^{\mathrm{cons}}_{HW,t,k}$	Average hourly hot water rate requirements during period t at node k [kW]
$\dot{Q}^{\mathrm{dimen}}_{H,k}$	Design size of the heating (and usually hot water) equipment implemented in building k [kW]
$\dot{Q}^{\mathrm{GT}^0}_{Exhst}$	Usable heat rate contained in the exhaust gas of the gas turbine, at full load [kW]
$\dot{Q}^{\mathrm{hn\_ww}}_{\mathrm{hs},t,k}$	Hourly heat rate delivered by the heating network to the water/water heat pump implemented at node k (if the temperature of the network is too low) during period t [kW]
$\dot{Q}^{\mathrm{loss}}_{t,k}$	Average hourly heat loss rate in the heating supply network during period t, compensated by the district energy conversion technologies located at node k [kW]
$\dot{Q}^{\mathrm{max}}_{H,k}$	Maximum heating and hot water rate requirement of node k (all periods included) [kW]
$\dot{Q}^{\mathrm{min}}_{H,k}$	Minimum heating and hot water rate requirement (greater 0) of node k (all periods included) [kW]
$\dot{Q}^{\mathrm{nb}}_{cn,t,k,d}$	Excess cooling rate transferred during period t from interval d to interval $(d-1)$ at node k in the network-building heat cascade [kW]

$\dot{Q}^{\mathrm{nb}}_{hn,t,k,d}$	Excess heat rate transferred during period t from interval d to interval $(d+1)$ at node k in the network-building heat cascade [kW]
$\dot{Q}^{\mathrm{net}}_{\mathrm{cs},t,d}$	Cooling rate requirements of the network during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{req}}_{C,t,d,k}$	Cooling rate requirements of the building at node k during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{net}}_{\mathrm{hs},t,d}$	Heat rate requirements of the heating network during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{req}}_{H,t,k,d}$	Average hourly heat rate requirements of the building at node k during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{req}}_{HW,t,k,d}$	Average hourly hot water rate requirements of the building at node k during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{tech}}_{ct,t,k}$	Hourly cooling rate delivered by the district energy conversion technology ct implemented at node k, during period t [kW]
$\dot{Q}^{\mathrm{tech}}_{ct,t,k,d}$	Hourly cooling rate delivered by the cooling district energy conversion technology ct implemented at node k during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{tech}}_{ht,t,k}$	Hourly heat rate delivered by the district energy conversion technology ht implemented at node k, during period t [kW]
$\dot{Q}^{\mathrm{tech}}_{ht,t,k,d}$	Hourly heat rate delivered by the heating district energy conversion technology ht implemented at node k during period t in temperature interval d [kW]
$\dot{Q}^{\mathrm{tn}}_{cn,t,d}$	Excess hourly cooling rate transferred during period t from interval d to interval $(d-1)$ at node k (provided a cooling district energy conversion technology is implemented at that node) in the technology-network heat cascade [kW]
$\dot{Q}^{\mathrm{tn}}_{hn,t,d}$	Excess hourly heat rate transferred during period t from interval d to interval $(d+1)$ in the technology-network heat cascade of the heating network [kW]
$\dot{Q}^{\mathrm{ww}}_{t,k}$	Hourly heat rate provided by the water/water heat pump during period t at node k for the heating and hot water requirements [kW]
r^{i}	Interest rate of a device i (in general) [-]
R^{gas}_{t}	Average hourly gas consumption rate during period t [kW]
R^{grid}_{t}	Average hourly electricity rate bought from the grid during period t [kW]
R^{oil}_{t}	Average hourly heating oil consumption rate during period t [kW]
S	Design size of a piece of equipment (in general) [kW]
S_{ct}	Design size of the district cooling technology ct [kW]
S_{ht}	Design size of the district heating technology ht [kW]
S^{aw}_{k}	Design size of the individual back-up air/water heat pump that needs to be implemented at node k [kW]
S^{boiler}_{k}	Design size of the individual back-up boiler that needs to be implemented at node k [kW]

S_k^{chiller}	Design size of the individual back-up chiller that needs to be implemented at node k [kW]
S^{GE}	Design size of the gas engine [kW]
S^{GT}	Design size of the gas turbine [kW]
$s_{H,k}$	Slope of the heating energy signature of building k [-]
S^{HP}	Design size of a district heat pump [kW]
$S_{\text{cn}}^{\text{pump}}$	Design size of the circulation pump of the cooling network [kW]
$S_{\text{hn}}^{\text{pump}}$	Design size of the circulation pump of the heating network [kW]
S^{ref}	Design size of a device (in general) taken as reference [kW]
S_k^{ww}	Required design size of the water/water heat pump that needs to be implemented at node k [kW]
$T_{\text{cr},t}$	Return temperature of the cooling network during period t [K]
$T_{\text{cs},t}$	Supply temperature of the cooling network during period t [K]
$T_{Cr,t,k}$	Return temperature of the cooling hydronic circuit of the building during period t [K]
$T_{Cs,t,k}$	Supply temperature of the cooling hydronic circuit of the building during period t [K]
$T_{\text{end},t}$	Temperature at the end of a one meter long pipe considering the heat losses during period t pipe [K]
T_g	Temperature of the ground in which the pipes are buried [K]
T_{H_2O}	Temperature of the water/steam in the heat recovery steam generator [K]
$T_{\text{hr},t}$	Return temperature of the heating network [K]
$T_{\text{hs},t}$	Supply temperature of the heating network [K]
$T_{Hr,t,k}$	Return temperature of the heating hydronic circuit of the building [K]
$T_{Hs,t,k}$	Supply temperature of the heating hydronic circuit of the building [K]
T^{atm}	Atmospheric temperature [K]
T_{Gas}^{comb}	Combustion temperature of the gas [K]
T^{cond}	Condenser temperature of a heat pump [K]
$T_{H,k}^{dimen}$	Minimum temperature for which the heating system in building k has been designed, to meet the heating requirements [K]
T^{evap}	Evaporator temperature of a heat pump [K]
T_t^{ext}	Average outside temperature during period t [K]
T_{Exhst}^{GT}	Temperature of the exhaust gas after the gas turbine, at part load [K]
$T_{Exhst}^{\text{GT}^0}$	Temperature of the exhaust gas after the gas turbine, at nominal load [K]

ΔT_{ct}	Temperature reduction generated by the district energy conversion technology *ct* in the district cooling network [K]
ΔT_{ht}	Temperature lift generated by the district energy conversion technology *ht* in the district heating network [K]
ΔT_{Exhst}	Minimum temperature difference between the exhaust gas and the water/steam in the heat recovery steam generator [K]
v	Velocity of the water in the pipes [m/s]
$X_{\mathrm{cr},i,j}$	=1 if nodes i and j are connected in the cooling return network and 0 otherwise [-]
$X_{\mathrm{cs},i,j}$	=1 if nodes i and j are connected in the cooling supply network and 0 otherwise [-]
$X_{\mathrm{hr},i,j}$	=1 if nodes i and j are connected in the heating return network and 0 otherwise [-]
$X_{\mathrm{hs},i,j}$	=1 if nodes i and j are connected in the heating supply network and 0 otherwise [-]
$X_{ct,k}$	=1 if the district cooling technology *ct* is implemented at node k and 0 otherwise
$X_{ht,k}$	=1 if the district heating technology *ht* is implemented at node k and 0 otherwise
$x_{ct,t}$	= 1 if the district cooling technology *ct* is operated during period t, 0 otherwise
$x_{ht,t}$	= 1 if the district heating technology *ht* is operated during period t, 0 otherwise
$X_{i,j}$	=1 if nodes i and j are connected (in the heating or cooling network) and 0 otherwise [-]
X_k^{aw}	= 1 if an individual back-up air/water heat pump is implemented at node k, 0 otherwise
X_k^{boiler}	= 1 if an individual back-up boiler is implemented at node k, 0 otherwise
X_k^{chiller}	= 1 if an individual back-up chiller is implemented at node k, 0 otherwise
$X_{\mathrm{cn},k}^{\mathrm{HEX}}$	=1 if a heat exchanger is implemented between the building at node k and the cooling network, and 0 otherwise [-]
$X_{\mathrm{hn},k}^{\mathrm{HEX}}$	=1 if a heat exchanger is implemented between the building at node k and the heating network, and 0 otherwise [-]
X_k^{ww}	= 1 if an individual back-up water/water heat pump is implemented at node k, 0 otherwise
X^{cn}	=1 if a district cooling network exists and 0 otherwise
X^{hn}	=1 if a district heating network exists and 0 otherwise
$Y_{\mathrm{cs},i,j}^{\mathrm{pipe}}$	=1 if a cooling network already exists in the district and has a connection between nodes i and j, and 0 otherwise
$Y_{\mathrm{hs},i,j}^{\mathrm{pipe}}$	=1 if a heating network already exists in the district and has a connection between nodes i and j, and 0 otherwise

$Y_{i,j}^{\text{pipe}}$	=1 if a network already exists (heating or cooling) in the district and has a connection between nodes i and j, and 0 otherwise
Y_k^{tech}	=1 if k is an eligible node to implement a district (plant) technology and 0 otherwise

Greek letters

γ	Calorific ratio ($\gamma = \frac{cp}{cv} = 1.4$) [-]
ϵ_{el}	Electric efficiency of a device (in general) [-]
$\epsilon_{\text{el}}^{ht}$	Electric efficiency of device ht [-]
ϵ^{grid}	Efficiency of the grid [-]
$\epsilon_{el}^{\text{GE}^0}$	Electric efficiency of the gas engine at nominal load [-]
$\epsilon_{\text{el}}^{GT^0}$	Electric efficiency of the gas turbine at nominal load [-]
$\epsilon_{\text{el}}^{GT}$	Electric efficiency of the gas turbine at part load [-]
$\epsilon_{\text{is}}^{Comp}$	Isentropic efficiency of the compressor [-]
$\epsilon_{\text{is}}^{GT}$	Isentropic efficiency of the gas turbine [-]
$\epsilon_{\text{is}}^{ST}$	Isentropic efficiency of the steam turbine [-]
ϵ_{th}	Thermal efficiency of a device (in general) [-]
$\epsilon_{\text{th}}^{ht}$	Thermal efficiency of device ht [-]
η^{hp}	Exergetic efficiency of small back-up individual back-up heat pumps [-]
η^{HP}	Exergetic efficiency of large district heat pumps [-]
κ_{ct}	Minimum possible part load for the district cooling technology ct [-]
κ_{ht}	Minimum possible part load for the district heating technology ht [-]
κ_{GT}	Part load fraction of the gas turbine [-]
λ	Friction coefficient in the pipes (= 0.02 [77]) [-]
π^C	Pressure ratio between the inlet and the outlet of the compressor [-]
π^{GT}	Pressure ratio between the inlet and the outlet of the gas turbine [-]
ρ	Density of the water in the pipes of the heating and cooling networks [kg/m3]
τ^C	Temperature ratio between the inlet and the outlet of the compressor [-]
τ^{GT}	Temperature ratio between the inlet and the outlet of the gas turbine [-]

Chapter 1

Introduction and motivation

1.1 Introduction

This chapter presents the motivation that led to the research work presented in this thesis, namely the development of a method to design and optimize district energy systems. District energy systems are believed to have a great potential to contribute to the reduction of greenhouse gas emissions linked mainly with heating, but also electricity and, increasingly, cooling. District energy systems represent, therefore, an option for a more sustainable development. However, designing an optimal district energy system that meets the energy requirements of a given district while minimizing CO_2 emissions and costs, requires a new dedicated methodology. The development of this methodology is the topic of the present thesis. However, before going directly into the details of the methodology, this first chapter introduces a few notions that help understanding some of the key points related to the issue of CO_2 emissions. After this introductory chapter, Chapters 2 to 4 explain in details how the methodology has been developed, and which algorithms have been used to solve the problem of the design and optimization of district energy systems. The application of the methodology is demonstrated in Chapters 5 and 6 where two case studies are presented. The first case is a virtual test case dedicated to the development of the methodology, and the second a real case in the Canton of Geneva. Chapter 7 takes some distance from the methodology for a short moment to present a novel type of district energy system based on CO_2 as working fluid, and compares this system to the more conventional water based district energy systems. Finally Chapter 8 concludes this thesis and gives a few hints for further developments.

1.2 Sustainability and sustainable development

In this section the notions of *sustainability* and *sustainable development* are introduced. The word ”sustainability” has become very popular in recent years, especially since the ratification of the Kyōtō protocol and it is used, as well, by politicians, leaders of the industry, leaders of non-profit organizations, and people in everyday life. However, the notions of sustainability and sustainable development are not new, and their origins can be dated back to as far as 1972. The important milestones that led from the very first environment programme of the United Nations, to the ratification of the Kyōtō protocol, including the definition of sustainability, are summarised hereafter.

1972 The first United Nations Conference dealing with sustainable development takes place in Stockholm [90]. The conference leads to the formation of the United Nations Environment Programme (UNEP), as well as to the "Declaration of Stockholm", and an action plan is set up that "defines principles for the preservation and enhancement of the natural environment and highlighted the need to support people in this process".

1980 The United Nations constitutes the World Commission on Environment and Development (Brundtland Commission).

1987 The World Commission on Environment and Development sets up the famous definition of what sustainable development is, namely: "a development which meets the needs of present generations without compromising the ability of future generations to meet their own needs".

1988 The Intergovernmental Panel on Climate Change (IPCC) which brings together hundreds of scientists to study, among others, the impact of human activities on the Earth's climate, is founded by the UNEP and the World Meteorological Organization (WMO).

1992 The first "Earth Summit" is held in Rio de Janeiro, Brazil, after climate change and the increase in "extreme weather events" [91] quickly becomes the major issue for leading organizations like the United Nations. This summit leads to a further action plan.

1994 The United Nations Framework Convention on Climate Change (UNFCCC) enters into force. This convention sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change [91].

1996 The IPCC publishes a report assessing the link between the warming of the earth's surface and the increasing concentration of greenhouse gas in the atmosphere. From there on, the mitigation of greenhouse gas becomes the priority for the United Nations Framework Convention for Climate Change.

1997 The Kyōtō Protocol is adopted. This protocol contains legally binding commitments (in addition to those included in the UNFCCC). The countries that sign the protocol agree to reduce their anthropogenic emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, and SF6) by at least 5% below 1990 levels in the commitment period 2008 to 2012.

2002 10 years after the Earth Summit of Rio, a "World Summit on Sustainable Development" is held in Johannesburg, South Africa. The result of this summit is a further action plan.

2005 The Kyōtō protocol becomes effective, 90 days after the fulfilment of both compulsory conditions: The protocol had to be ratified by at least 55 countries, representing at least 55% of the CO_2-emissions emitted by the industrialised countries.

From 1972 till today, the notion of sustainability thus gradually gained some importance. The awareness increased, that "addressing climate change and the activities causing climate change is a key challenge for the 21st century, for both developed and developing countries, if sustainable development is to be attained", as stated by the European Environment Agency in 2002. Examples of this awareness can be found in the various programs, laws and action plans that are set up not only on the worldwide level of the United Nations, but also on local levels (SuisseEnergie[1] for instance in Switzerland or Berliner Energietage in Germany to mention two), or in private companies.

Sustainable behaviour can be applied in many different areas, like for instance industrial processes, agriculture, urban development, human behaviour and leisure, to mention a few. Table 1.1 gives for each of these areas an example of what sustainable acting would be versus non sustainable acting, considering the definition of sustainability given above. Further examples can be found in [34].

Although the link between climate change, sustainability and greenhouse gas emissions has been assessed by the United Nations, based on the works of hundreds of researchers around the world, it is worth noticing that the importance of the influence of greenhouse gas emissions on the climate change is still much debated by a few researchers (see for instance Khandekar [59]). It is however in the opinion of this author that it would not be responsible to take the risk of remaining inactive.

Figure 1.1 shows the evolution of the CO_2 emissions in some selected countries, in tons per capita [91]. The United States of America and Australia have been chosen because they belong to the most emitting countries in the world[2], and both did not ratify the Kyōtō protocol. Japan and France belong to the most industrialised countries in the world (together with the United States of America) but both ratified the Kyōtō protocol. Sweden has been chosen because it is a leading country in Europe for the implementation of district energy systems, and Austria represents a good comparison to Switzerland, both in size and structure of the country, as to the policies adopted for the promotion of renewable energy sources or the rational use of energy. Finally, the two big upcoming economies China and India are also represented. The projection for the year 2012 shown in dotted lines, represent the objectives set by the Kyōtō protocol for the selected countries. China and India having been considered as developing countries, no specific target has been set by the Kyōtō protocol for these two countries. Among the developed countries, one can see that since 1970, Australia, Austria and Japan have an increasing trend, while Sweden and France show a decreasing trend and Switzerland remains stable.

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[1] This action plan was started in 2001 and sets targets that have to be met by the year 2010, such as for instance the yearly increase in electricity consumption that shall not exceed 5%, or the fact that the generation of electricity with renewable energy sources shall increase by at least 1% per year and that of heat by at least 3% per year [44].

[2] Australia finally ratified the Kyōtō protocol at the very end of the present thesis...

	Non sustainable acting	Sustainable acting
Industrial processes	Reject excess high value heat	Integrate the processes in order to recycle excess heat from one process into another process
Urban development	Build buildings too close to each others	Leave space between buildings for plants to grow and sunlight to light up the rooms
Human behaviour and leisure	Use a private car	Use public transportation
Agriculture	Intensive use of fertilizer	Let the land lie fallow from time to time

Table 1.1: Examples of sustainability in different sectors

Sweden, France and Switzerland are the least emitting developed countries, followed by Austria and Japan. Australia and the United States emit about 4 times more than Switzerland in 2005. The emerging economies China and India are the least emitting countries, but show an increasing trend (especially China).

Figure 1.2 shows the shares of the different greenhouse gases for 1990 and 2005 in CO_2-equivalent for Switzerland [91]- [87]. Among the different greenhouse gas emitted by human activities, CO_2 is clearly the most important gas with approximately 80% of the total emissions. Although the figures are given for Switzerland, the same observation is valid for the major part of the industrialised countries. It can therefore be considered sufficient to focus the study on the decrease of CO_2-emissions when it comes to find new solutions for more sustainable energy systems, even if CO_2 has the lowest Global Warming Potential among all the registered greenhouse gas, as can be seen in Table 1.2[3]. Not only do CO_2-emissions represent by far the largest part of the emissions, but decreasing CO_2-emissions will inevitably have a positive impact on other much emitted gas such as N_2O. Almost all greenhouse gases, except CH_4 as well as the HFCs and PFCs, are indeed generated by combustion processes. By avoiding the combustion of highly CO_2 emitting fuels, the emissions of the other gas will therefore decrease as well.

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[3] The Global Warming Potential (GWP) has been defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (usually CO_2) [55]. This factor is for instance very much used in Life Cycle Analysis.

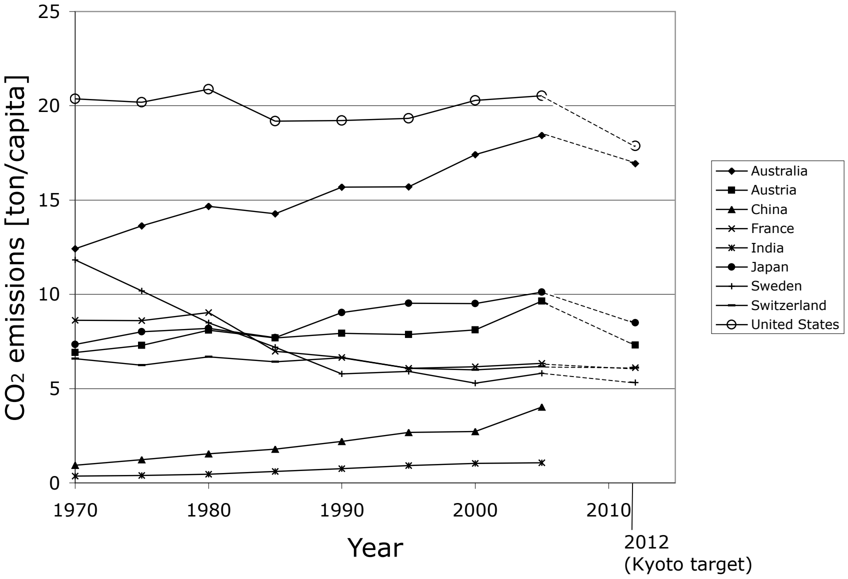

Figure 1.1: CO_2 emissions in ton per capita for some selected countries, including the target set by the Kyōtō protocol (2012) [91]

In Switzerland, more than 40% of the total distributed energy is dedicated to heating purposes [69]. Considering the fact that the generation of electricity in Switzerland is almost free of CO_2 emissions (nuclear and hydraulic power being used), the CO_2 emissions due to heating can be evaluated to almost 60%, the rest being imputable to transportation (diesel and petrol). Heating is therefore a priority candidate among *energy services* when considering ways to decrease the overall emissions of Switzerland[4]. Figure 1.4 shows the share of CO_2 emissions generated by the different distributed energies.

1.3 Equation of Kaya

The link between sustainability and CO_2 emissions was first put in the form of an equation by Holdren and Ehrlich in 1974 [52]. More recently, Kaya proposed a new formulation (1989) which became famous under the name of *equation of Kaya*, thus emphasizing the multiplicative effect of the different factors influencing the environmental deterioration:

$$CO_2 = Pop \cdot \frac{GDP}{Pop} \cdot \frac{En}{GDP} \cdot \frac{CO_2}{En} \qquad [\text{ton-CO}_2] \tag{1.1}$$

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[4] The other big candidate being of course transportation.

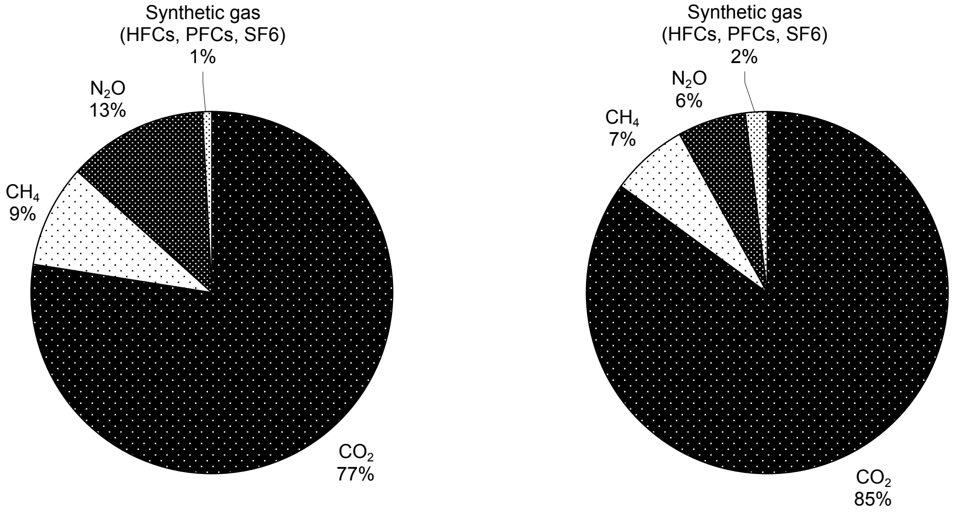


Figure 1.2: Shares of the greenhouse gas emissions in CO_2 equivalents for Switzerland for 1990 (left) and 2005 (right) [87, 91]

with:

Pop	population [capita]
GDP	gross domestic product [CHF]
En	energy consumption [J]
CO_2	CO_2 emissions [ton-CO_2]
$\frac{GDP}{Pop}$	living standard [CHF/capita]
$\frac{En}{GDP}$	energy intensity [J/CHF]
$\frac{CO_2}{En}$	carbon intensity [ton-CO_2/J]

The annual growth rate of CO_2 emissions is given by differentiation of Equation 1.1 as the sum of the growth rates of the respective four components: population growth, living standard, energy intensity and carbon intensity. *Population growth* has a direct quantitative effect on the evolution of the volume of CO_2 emissions. An increase of the *living standard* is currently synonymous of a higher volume of CO_2 emissions, other things being equal, since activity and comfort demand increase with economic development. The evolution of the *energy intensity* relates to structural and technological changes of the system considered. And finally, the evolution of the *carbon intensity* is a metric which indicates changes in the mix of energy sources [14].

Figure 1.3 shows the evolution of the GDP, the population, the final energy consumption and the CO_2 emissions in Switzerland since 1975 [44]. The evolution of the CO_2 emissions is a result of the decreasing carbon intensity of industrial processes but also of a trend of western European countries to translocate CO_2-intensive production processes abroad, and to keep the services trade in the country [44]. This explains why the CO_2 emissions in Switzerland do not increase, according to the equation of Kaya, with the increase in population and living standard that occurred in Switzerland over the last decades. One has therefore to regard these figures with caution, since they do not reflect the CO_2 emissions generated by the Swiss population in other countries.

Gas	GWP
CO_2	1
CH_4	23
N_2O	296
HFC-23	12'000
HFC-125	3'400
HFC-134	1'100
HFC-143a	4'300
HFC-152	43
HFC-227ea	3'500
HFC-236fa	9'400
CF_4	5'700
C_2F_6	11'900
SF_6	22'200

Table 1.2: Global Warming Potential (GWP) of the different greenhouse gases, using CO_2 as reference [55]

Considering the equation of Kaya, there are two reasonable ways to decrease CO_2-emissions: reduce the energy intensity, or reduce the carbon intensity. The reduction of energy intensity can be achieved by implementing more efficient processes (improve industrial production processes with increased process integration, decrease the petrol consumption per kilometre driven for a car by using hybrid engines, increase the insulation thickness in a house, and many more). The reduction of the energy intensity is often coupled with higher investment or refurbishment costs, however these higher costs are usually compensated by lower operating costs [53]. The reduction of the carbon intensity can be achieved for instance by the use of renewable energy sources, or the integration of a CO_2 capture step in an energy conversion process generating CO_2 emissions.

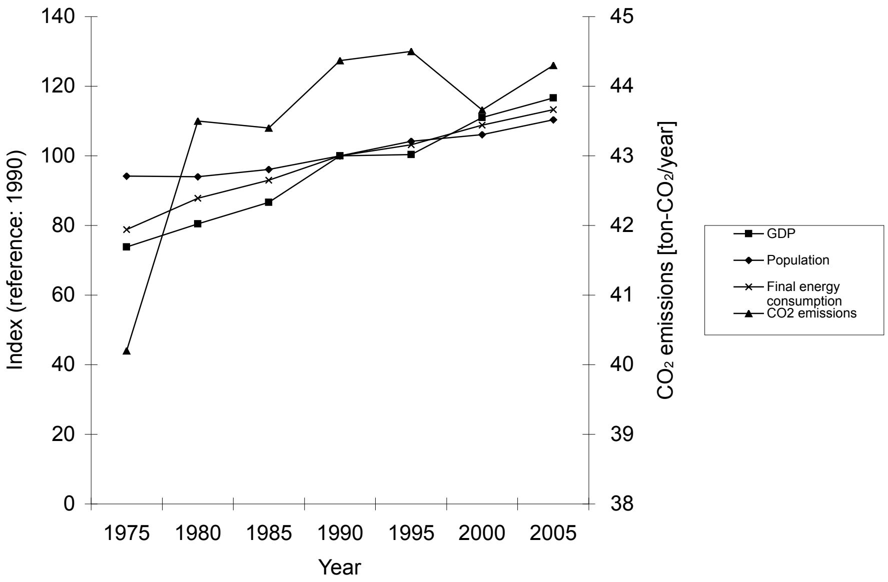


Figure 1.3: Evolution of the GDP, the population, and the final energy consumption (left Y-axis), as well as the CO_2 emissions (right Y-axis) in Switzerland between 1970 and 2005 [16, 46]

1.4 Energy related definitions

At this stage, it is important to give following energy related definitions (following Haldi et al. [50]), that will be used throughout this manuscript:

Primary energy Energy as encountered in nature (fossil fuel deposit, flowing water, wind,...) that contains energy that can not readily be used without being first transformed.

Intermediate energy Energy that is conditioned for distribution.

Distributed energy Energy as bought by the end-user and that can be used directly as raw material in an energy conversion technology to provide the required energy service (car fuel, electricity, home delivered heating oil,...).

Energy service Energy linked to the expected end-use service, providing the comfort sought-after (heating at the requested temperature level to have a comfortable warm building, light, operating computers,...),

Primary energy, intermediate energy, distributed energy and energy service may be seen as the different stages covered by the energy before it ends up as low graded energy in the environment. Examples for each of the definitions are given in Figure 1.5 starting from different types of primary energies, namely uranium, oil, natural gas, forest, wind, damned water and waste (the list is not exhaustive). Uranium,

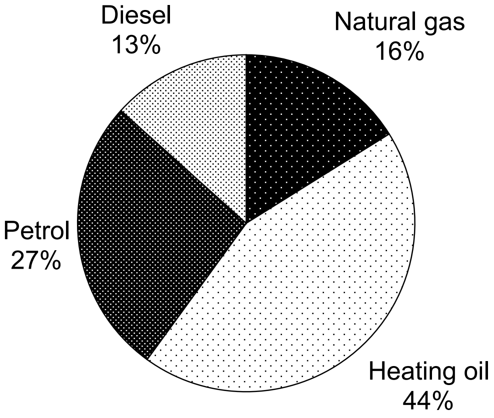


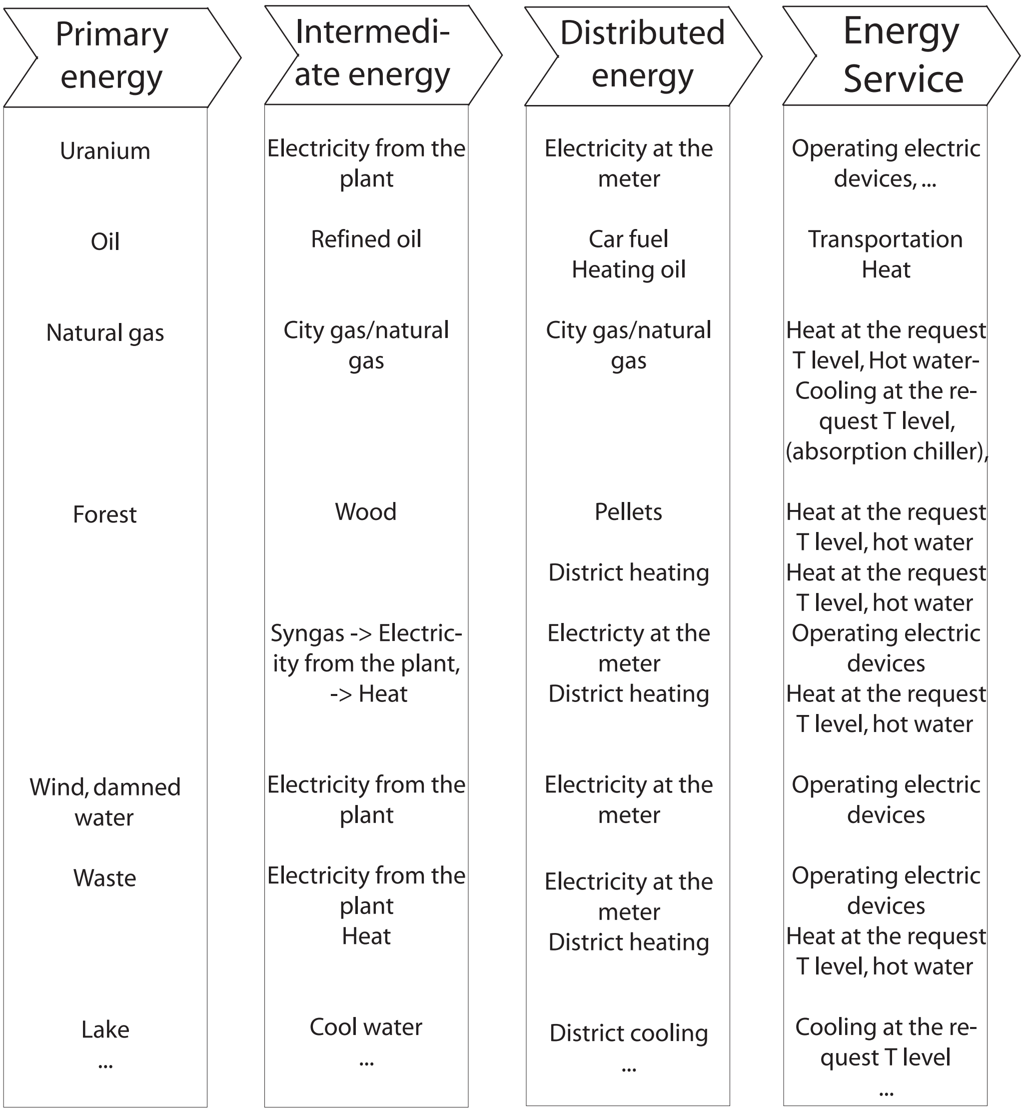
Figure 1.4: CO_2 emissions in Switzerland for 2005 according to the fuel type [89, 70]

for instance, can be used in a nuclear power plant to generate electricity that finally provides light. Natural gas can be extracted, purified and dried, if necessary, to obtain city gas that can be distributed to provide heat at the requested temperature level. Note that the term *natural gas* is often used to designate not only the primary energy, but also the intermediate and the distributed energies. Trees of a forest can be transformed into wood which, in turn, is transformed into pellets to provide heat and hot water, or syngas which, in turn, is transformed into electricity and heat to power devices and heat up dwellings.

Besides these definitions, it is important to note the following points regarding this manuscript:

- By misuse of language and to keep it shorter, the term *electricity* is usually used to express both the distributed energy and the energy service, although the energy service corresponding to electricity should be *operating devices* (light or operating computers for instance). In this manuscript, following this general trend, the term *electricity* will be used instead of the term *operating devices.*
- Again by misuse of language, and to keep it shorter, the terms *heating* and *cooling* will often be used in this manuscript to designate the energy service corresponding to "heating at the requested temperature level to have a comfortable warm building" and "cooling at the requested temperature level to have a comfortable cool building". Besides, regarding *heating* it can be used to designate the energy related to the sole heating requirements of the buildings, or else to designate both the heating *and* the hot water related energy (like in the expressions *heating network*, which expresses the network that transfers the heat to the buildings for both heating and hot water requirements). The way the term *heating* shall be understood, will be clear from the context or else specified. Finally, regarding cooling, only air-conditioning is considered and no refrigeration (except in Chapter 7 where it is explicitly mentioned)

- Since the term *city gas* is less used than the term *natural gas*, this latter term will be used throughout this manuscript to designate the intermediate and the distributed energies.
- Instead of the expression *to provide an energy service*, the equivalent expression *to meet/satisfy an energy requirement* will sometimes be used.



Primary energy	Intermediate energy	Distributed energy	Energy Service
Uranium	Electricity from the plant	Electricity at the meter	Operating electric devices, ...
Oil	Refined oil	Car fuel Heating oil	Transportation Heat
Natural gas	City gas/natural gas	City gas/natural gas	Heat at the request T level, Hot water- Cooling at the request T level, (absorption chiller),
Forest	Wood	Pellets	Heat at the request T level, hot water
		District heating	Heat at the request T level, hot water
	Syngas -> Electricity from the plant, -> Heat	Electricty at the meter District heating	Operating electric devices Heat at the request T level, hot water
Wind, damned water	Electricity from the plant	Electricity at the meter	Operating electric devices
Waste	Electricity from the plant Heat	Electricity at the meter District heating	Operating electric devices Heat at the request T level, hot water
Lake ...	Cool water ...	District cooling ...	Cooling at the request T level ...

Figure 1.5: The energy chain with the different classification categories (after [50])

1.5 Energy services in cities and polygeneration

In Section 1.2 it was shown that the energy service heating contributes to almost 60% of the CO_2 emissions in Switzerland. However, considering heating only, without simultaneously looking at other energy services like electricity for instance, bears the risk to miss low (or less) CO_2 emitting concepts which would be interesting on an energetic point of view. Polygeneration energy conversion technologies, indeed, satisfy different energy services simultaneously. By doing so, they help decreasing the CO_2 intensity compared to energy conversion technologies that meet only one energy service, as will be shown further down this section as well as in Section 1.6. On the other hand, beside defining the energy service(s) for which actions can/need to be undertaken (like heating for instance), it is also important to define *where* these actions can/should take place. In this respect, cities are more appropriate than less populated areas. Because of their dense population, modern cities are faced with major challenges regarding the satisfaction of the energy requirements and the related CO_2 emissions. Cities can be considered therefore an early-warning indicator of environmental impacts, with problems emerging faster than elsewhere [13]. For example, in the city of Geneva the actual population density amounts to 11'500 inhabitants/km^2 [71] and the trend is increasing. Such densely populated areas require large amounts of distributed energies to meet the different requirements in terms of heating, hot water, cooling and electricity, as well as large amounts of car fuel. Table 1.3 gives an illustrative example of the consumption of distributed energies for the Canton of Geneva, for the year 2005. Beside these distributed energies, large amounts of sewage water and waste have to be treated, that contain high energetic potentials that can be exploited[5]. Table 1.4 shows that the amount of waste treated in 2005 in the Canton of Geneva.

Distributed energy	Annual total	Annual per capita	Hourly per capita[6]	Annual CO_2 emissions per capita
Electricity	10 056 TJ	22 785 MJ	0.72 kWh/h	696 kg[7] 2 848 kg[8]
Natural gas	8 891 TJ	20 145 MJ	0.64 kWh/h	1 287 kg
Heating oil	12 746 TJ	28 880 MJ	0.92 kWh/h	2 351 kg
Coal	106 TJ	240 MJ	~ 0 kWh/h	40 kg
Car fuel	9 959 TJ	22 565 MJ	0.72 kWh/h	1 570 kg

Table 1.3: Distributed energies consumed in the Canton of Geneva in 2005 [71]

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[5] The waste incineration plant *Les Cheneviers* in Geneva, that generates electricity and district heating (*Cadiom*) , illustrates this.

	Disposal type	Annual total	Annual per capita	Energy per capita
Waste	Incinerated	213 122 to	483 kg	1 596 kWh/year[9]
	Recycled	487 629 to	1 106 kg	-
Sewage water		$79\,000\,000\,m^3$	$179\,m^3$	2 077 kWh/year[10]

Table 1.4: Disposals treated in the Canton of Geneva in 2005 [71]

Beside being an early-warning indicator of environmental impacts, cities feature an important emission reduction potential. Any action undertaken in a large city to mitigate emissions will indeed have significantly more impact than the same action undertaken elsewhere. This is particularly true for energy services.

To provide the energy services of the different buildings in a city, there are basically two possibilities:

1. Use individual energy conversion technologies in each building.
2. Use centralized energy conversion technologies that meet the requirements of a large city or even a whole country, together with a distribution network.

The use of individual energy conversion technologies (solution 1) prevails in the western European countries for energy services such as heating, hot water and cooling. Examples of such technologies are mainly boilers, but also heat pumps and individual air conditioning units. The main characteristic of these technologies is that they are easy to handle and do not require the proximity to the primary energy source. The use of centralized energy conversion technologies, on the other hand, prevails for electricity, with the large nuclear, hydraulic or coal power plants. They require professional control and, in some cases, a direct access to the primary energy source (hydraulic plant), making it therefore obvious for people today to have a network for the distribution of the electricity from a power plant to the consumers. For heating, hot water and cooling the use of a distribution network is still very rare. In Switzerland, only 4% of the entire heating requirements are met by district heating networks [69]. It is only in some specific cases, when the recycling of heat generated by the combustion of city waste allows it (Cadiom in Geneva), or that the combustion of biomass (wood) near a forest justifies it [23], that a heating network is

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[6] According to [50] the actual Swiss average energy consumption amounts to 6 kWh/h per capita, including the grey energy. The sum of all the distributed energies consumed in the Canton of Geneva amounts to 3 kWh/h, which is below the Swiss national average. This can be explained among others by the fact that the 3 kWh/h don't include the grey energy, or else that the Canton of Geneva doesn't host any high energy consuming industry (chemical industry for instance).

[7] Swiss mix: 0.11 kg-CO_2/kWhel

[8] UCTE mix: 0.45 kg-CO_2/kWhel

[9] Considering a heating value of 3.305 kWh/kg [22]

[10] Considering that a ΔT of 10°C can be exploited

implemented to use this heat. Regarding the cooling requirements, they are usually met by individual electric chillers (where allowed[11]).

The major drawback of having some of the energy services provided by individual energy conversion technologies at the building level (boilers for instance), and others by centralized energy conversion technologies at national level (nuclear power plant for instance), is that the implementation of efficient, integrated, polygeneration energy conversion technologies is hindered. Polygeneration energy systems are systems that generate more than just one single energy service. Examples of such systems are combined cycles including a gas turbine and a steam turbine, or fuel cells. These systems generate both electricity and heat. Another example of polygeneration energy system generating also cooling (beside heating and electricity), includes fuel cells integrated with absorption-chillers. Polygeneration systems feature better overall efficiencies when converting primary or distributed energies to the final requested energy services, than if the same energy services are provided by a serie of single, individual or centralized, energy conversion technologies. Due to their higher efficiencies, polygeneration energy systems can play a major role to decrease CO_2 emissions. It is indeed also important to note that even when using renewable energy sources such as biomass or waste, the advantage of being renewable or even "CO_2 neutral" (biomass[12]) shall not exempt the engineers from searching efficient technologies, such as polygeneration energy conversion technologies, to convert these energy sources into energy services. However, to ensure that polygeneration systems operate as often as possible at or near their optimal load, they should be implemented so as to meet the requirements of more than just one building. By doing so, it is possible to take advantage of the various load profiles of the buildings by compensating the fluctuations and having therefore a smoother operation. It is only in some cases that polygeneration energy systems are appropriate for a single building, namely if this building is large (skyscraper for instance) and houses different allocations like hotels, department stores, office buildings,... (see Section 1.6). Besides, since these systems are complex and de-facto difficult to operate, they are usually not justified in an individual building where no continuous professional control can be guaranteed. It is much more advantageous to implement them in a small plant that serves several buildings, or a district, and that is managed, for instance, by an energy service company. However, the definition of the number of buildings that shall have their energy services met by a polygeneration energy conversion technology is not a trivial task. Implementing polygeneration energy systems for a whole country for instance, results in too large heat losses and pressure drops, not to mention the security of supply in case of failure. Polygeneration energy systems are therefore appropriate for districts or small cities, where they can help wipe out the following disadvantages of both individual and centralized energy conversion technologies, beside contributing to decrease CO_2 emissions:

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[11] In the Canton of Geneva, individual air conditioners are forbidden.

[12] Although biomass is often considered as being CO_2 neutral, note that this is only true if the transportation of the biomass is not considered.

1. Individual energy conversion technologies:
    - take space in the building that could otherwise be used more effectively (especially boilers that require space for the oil or gas storage),
    - lack good efficiencies compared to their larger counterpart (the exergetic efficiency of a small single family house heat pump for instance amounts to about 40% [105], compared to 60% for larger heat pumps of several MW [75], individual chillers on the other hand have even been prohibited in some cantons of Switzerland due to their low efficiencies and high electricity requirements),
    - have to follow the exact consumption profiles of the building for each of the energy services (unless there is a little storage tank), preventing from a smooth operation.
    - represent an important source of emission in densily populated areas (in the case of individual boilers for instance).
2. Centralized energy conversion technologies:
    - imply transmission losses due to the energy transfer between the plant and the consumers,
    - represent an issue in terms of security of supply (for instance in case of a breakdown),
    - can lack acceptance among the population because people are not ready to give up the idea of the individual energy conversion technology on which they have the entire control, for a more centralized solution.

In the following, an example of the way a polygeneration energy conversion technology can help mitigating CO_2 emissions is illustrated. The polygeneration energy system includes a gaz turbine combined cycle coupled with a heat pump, to provide heating. This system shall be compared to a conventional boiler, for a heating requirement of 100 units of energy. Let us assume the following efficiencies:

Boiler	$\epsilon_{\mathrm{th}} = 0.9$
Gas turbine combined cycle with cogeneration [73]	$\epsilon_{\mathrm{el}} = 0.5$
	$\epsilon_{\mathrm{th}} = 0.4$
Heat pump[13]	$COP = 3.5$

The amount of natural gas required by each system to meet the requested heating requirement is given in Figure 1.6. As can be seen, the boiler requires 111 units of energy whereas the combined cycle coupled with the heat pump requires only 46.5 units of energy, thus resulting in an energy saving (and therefore a CO_2 emissions reduction potential) of 57%. Another way to look at this issue is to compute the energy that could be obtained by giving the 111 units of natural gas to the combined

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[13] Average value of different systems [75]

cycle coupled with the heat pump, instead of giving them to the boiler. In this case, the polygeneration system could provide 100 energy units of heat and an additional 40 energy units of electricity. This example clearly shows the advantage of using polygeneration, and specially the benefit that can be gained by combining polygeneration systems with heat pumps. Heat pumps indeed make an efficient use of the energy available in the environment and are therefore assigned an important role in the heating sector when it comes to decrease CO_2 emissions. Further polygeneration examples and their respective energetic and exergetic efficiencies are given in Figure 1.7.

If the combined generation of heat and power is currently the most used polygeneration system, the integration of cooling in polygeneration systems is of utmost importance when considering a rational use of energy. Cooling is indeed becoming a major issue even in countries like Switzerland, Finland [85] or Denmark [88].

The energy services considered in this thesis include heating, hot water, cooling and electricity.

An example of a study including the design and operation optimization of a polygeneration energy system is shown in the following section. Even though the example is given for a large standalone office-building, that justified the implementation of such a complex system, this type of system could as well serve a group of buildings (a small district). The study presented was conducted for an office-building downtown Tōkyō [99] and [100]. However, the method developed for the study as well as the basic ideas underlying the study (namely the use of ploygeneration energy system) remain valid for any other location.

1.6 Polygeneration energy system in an office-building

In the study presented in this section ([99] and [100]), the goal was to analyse the potential of a polygeneration energy system to decrease the CO_2 emissions linked to the energy services for an office building (compared to conventional energy systems including boilers, electric chillers and electricity from the grid), and at what cost this CO_2 emissions reduction could be achieved. The polygeneration energy system includes a solid oxide fuel cell based system comprising the following technologies (see Figure 1.8):

1. a solid oxide fuel cell (SOFC) for electricity and heat (via the heating storage STH),
2. a double-stage absorption chiller (AC2) and a single-stage absorption chiller (AC1) for cooling purposes (via the cooling storage STC),
3. two storage devices (for heating: STH, and for cooling: STC).

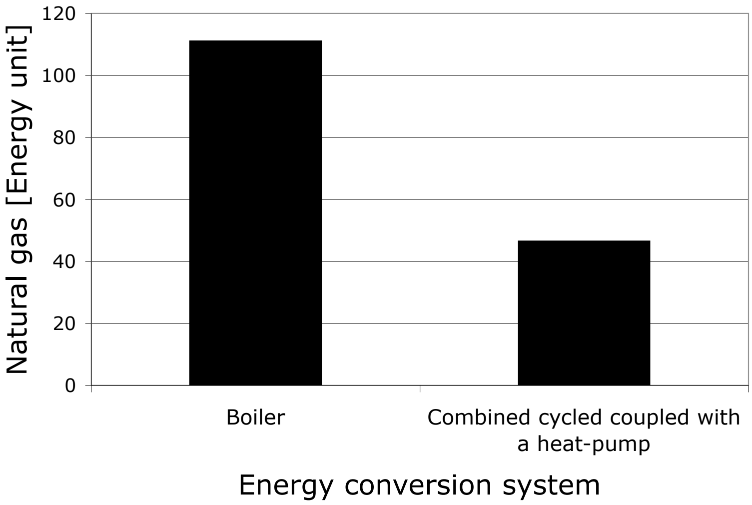

Figure 1.6: Natural gas requirements requested to provide 100 energy units of heating

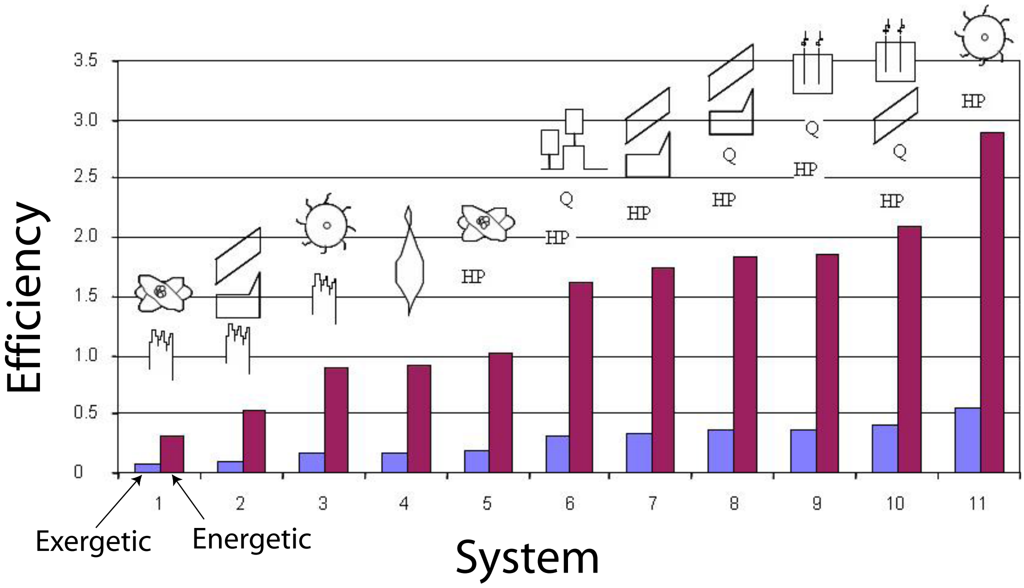

Figure 1.7: Different polygeneration systems with their respective energetic and exergetic efficiencies for heating [35] (Grid heat losses: 4%, Network thermal losses: 5%, Heat pump first law efficiency: 3.33, Heat pump second law efficiency: 0.65%, Network temperature: 65°C, Atmospheric temperature: 0°C, Cogeneration unit thermal losses: 10%): 1. Nuclear power and direct electric heating, 2. Electricity from a combined cycle power plant and direct electric heating, 3. Hydraulic power and direct electric heating, 4. Boiler, 5. Nuclear power and heat pump, 6. Electricity from a cogeneration engine and heat pump, 7. Electricity from a combined cycle power plant and heat pump, 8. Electricity from a combined cycle with heat recovery and heat pump, 9. Electricity from a cogeneration fuel cell and heat pump, 10. Electricity from a hybrid plant including a fuel cell and a natural gas combined cycle with heat recovery and a heat pump, 11. Hydraulic power and heat pump.

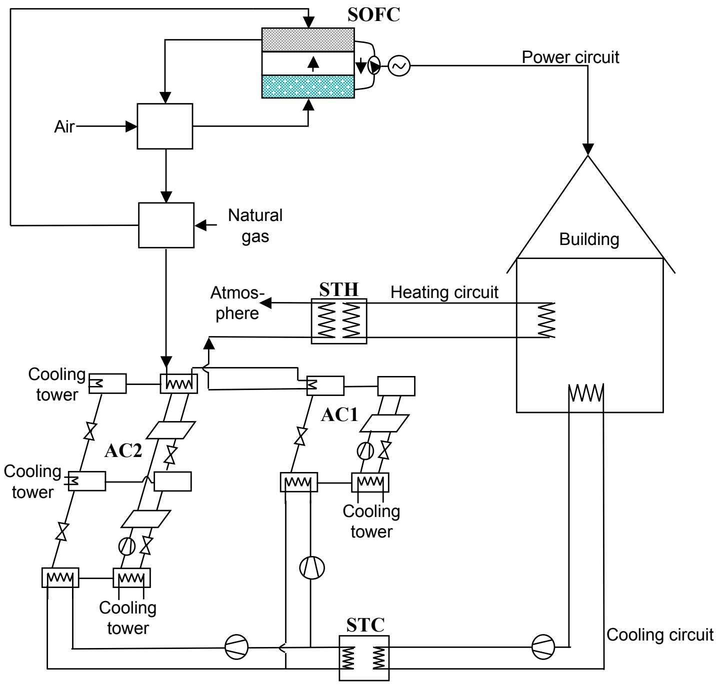

Figure 1.8: Solid oxide fuel cell based polygeneration system for an office-building downtown Tōkyō (after [100])

The choice of the solid oxide fuel cell as basis technology is justified by the large interest shown by Japanese people for what is considered in Japan to be a very promising technology [56, 46, 61]. Solid oxide fuel cells generate electricity, that can be used directly in the building in which the system is implemented, and heat (hot exhaust gas) that can be used either to activate absorption-chillers during the hot and humid Japanese summer, or for heating purposes in winter. The exhaust gas from the SOFC circulates through the double stage absorption chiller, the single stage absorption chiller and/or the heat storage. If no heating is required or if one of the absorption-chillers is not necessary, the exhaust gas by-passes the respective device. If neither heating nor cooling is required, the exhaust gas is directly released to the atmosphere, by-passing all the devices. (The by-passes have not been depicted on Figure 1.8, to avoid overloading the figure.)

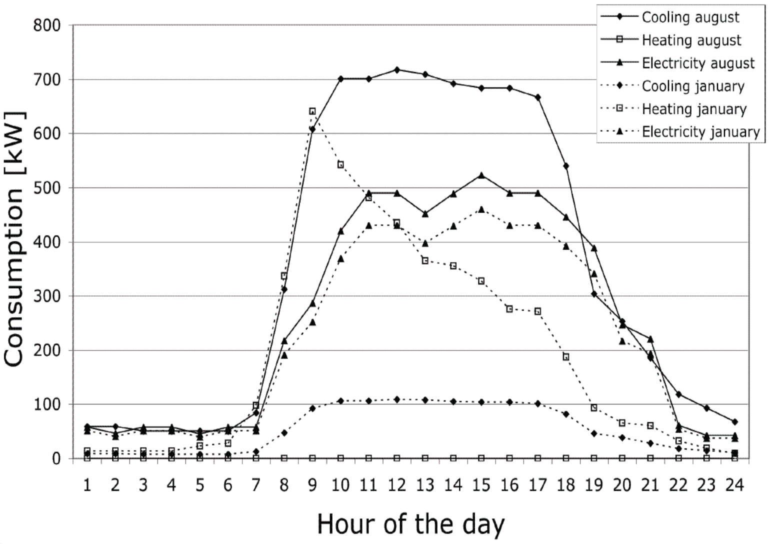

Figure 1.9: Electricity, cooling and heating requirements of the office building in Tōkyō for January and August [100]

1.6.1 Description of the building conditions

For the purpose of the study, the following building conditions are used:

1. 20 story office building (with 200 office-rooms),
2. 50 m^2 per office-room,
3. 7 persons working in each office room,
4. 12 working hours per day (from 08:00 to 20:00),
5. 5 working-days per week, minus official Japanese holidays.

The consumption profiles for the building have been computed based on measured data [60]. For each month, one representative day has been chosen. Figure 1.9 shows for instance the profiles for January and August. The following assumptions have been made for the building energy demands:

1. The electricity requirements for lighting and electric appliances are the same in each office room and remain constant throughout the working-day. These electric requirements do not include the electricity requirements for the cooling and heating of the building.
2. Japanese offices typically use an electric water-heater to provide hot water, which is included in the "base electricity demand". Therefore, there is no hot water requirement.
3. The electricity requirements at night (i.e. for server computers, refrigerators, etc.) is assumed to be 10% of the daytime requirements.

Regarding the energy conversion technologies, the following assumptions were made:

1. All the efficiencies and coefficients of performance are assumed constant, regardless of the part load factor.
2. The SOFC cannot be operated at a part load smaller than 30%.
3. The values for the emissions and the costs (electricity from the grid, manufacturing of the devices, gas) are specific to the city of Tōkyō.

1.6.2 Resolution strategy and results

The resolution strategy developed to compute the performances of the polygeneration energy system in terms of yearly CO_2 emissions and yearly costs is divided in two levels: the equipment design level, and the performance computation level. In the design level, a multi-objective optimizer is used to optimize the sizes of the storage devices, the size and configuration parameters of the SOFC, and the sizes and configuration parameters of the absorption-chillers. The performance of the system is then computed for the 12 representative daily load profiles, considered to represent the annual range of hourly electricity requirements, heating loads, and cooling loads for the analyzed office building. This resolution strategy was the starting point for the method developed in the present thesis for district energy systems, that will be explained in further details in Chapters 2 to 4.

The study showed that the integrated energy system presented above allowed to reduce CO_2 emissions by about one third compared to a conventional energy system that uses electric chiller-heaters for cooling and heating demands and takes all electricity from the grid. The CO_2 emissions generated in the integrated energy system are mainly due to the operation of the SOFC. The limit in the CO_2 savings potential of the given integrated energy system is given by the amount of CO_2 emitted by the SOFC. Note that in this study, the size of the building does not have much influence on the CO_2 emissions reduction potentials, because the energy consumption profiles have been assumed to vary linearly with the size of the building. The price to pay in order to achieve these CO_2 emissions reduction is still very high, due to the high costs of solid oxide fuel cells: an increase of about 70% compared to the conventional system.

1.7 District energy systems and the need for a new design method

In the previous section it was shown how an integrated polygeneration energy system could help mitigating CO_2 emissions for a large office building. It is important to stress that in order for such a system to be viable, especially when considering electricity requirements, the following conditions have to be taken into account:

1. The sizing of the equipment becomes of utmost importance for two reasons. First, because the system is *integrated*, the different pieces of equipment have to match. Second, because the investment costs of such systems are high, an excessive "over-sizing" can rapidly increase the costs in a senseless way. These two aspects differ much from conventional systems for which electricity is taken from the grid and heating is provided by a boiler. For the consumer, the investment costs of these latter systems are low. This often results for instance in boilers being sized too large, since the "over-size" does not increase the investment costs much when dealing with boilers, but gives a feeling of "being on the safe side" to the consumer.

2. The energy consumption profiles of the supplied building(s) have to be of the order of magnitude of the design size of the implemented polygeneration energy conversion technologies, several hundreds of kilowatts for a gas engine, several tens or hundreds of megawatts for a gas turbine combined cycle to mention but a few. Otherwise, the technologies will not have reasonable electrical efficiencies ($\geq$ 40% electric efficiency at design load for gas engines or 48-54% for gas turbine combined cycles with municipal heat recovery [41]).

3. The integrated polygeneration energy system should ideally meet the energy requirements of an entity featuring various different energy consumption profiles such as a group of buildings, or else a very large building (skyscraper) housing different types of allocations such as hotels, offices, department stores,... as you can find them in Tōkyō. The benefit for the polygeneration energy conversion system of having different consumption profiles is to take advantage of the fluctuations of the profiles to smooth the operation, and therefore operate as often as possible at or near the optimal part load.

4. Continuous professional control of the complex integrated polygeneration energy system should be guaranteed.

Note that in Switzerland, the large buildings mentioned in Point 3 are not yet very common, and therefore polygeneration energy systems are more likely to be implemented so as to meet the energy requirements of a group of buildings or a district. The rest of this manuscript will therefore concentrate on this latter case[14].

When having a group of a few buildings, up to a whole city (especially a small city in the size range of Swiss cities), with its thermal and electrical energy requirements met by an integrated polygeneration energy system, a distribution network will be required. For electricity the existing grid can be used, but for heating (including hot water) and cooling, distribution networks need to be designed. The resulting system will be called hereafter a *district energy system.*

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[14] It is important to stress that if the method has been developed based on Swiss districts, it remains, nonetheless, valid for any district in any country.

A district energy system, is a system comprising one or more integrated polygeneration energy conversion technologies, together with the required distribution network(s), fulfilling the task of providing energy services (heating, hot water, cooling and/or electricity) for more than one building.

Note that with the given definition of a district energy system, a district can be of any size, starting from two buildings.

Despite the advantages of district heating and cooling, related to the high efficiencies of the polygeneration energy systems that can be implemented, district energy systems still have a hard time emerging in countries like Switzerland. The main reasons for this can be summarized as follows:

1. As already mentioned, people prefer relying on their own system (boiler for instance) rather than having a system which is out of their control. The picture is different for electricity because the processes used up to now to generate electricity are much more complex than a simple combustion and require large installations (nuclear power plant) or technologies located at specific places (dams).
2. In Switzerland, the owner of the dwelling is often not the inhabitant, so that considerations such as space availability, namely the space "lost" for the gas or heating oil tank, are not taken into account when choosing the heating system [67].
3. District energy systems require high investment costs.

However, if district energy systems are required to play an important part in the reduction of CO_2 emissions, one must bear in mind that before implementing such a system, it is important to study its relevance for the analysed district. District energy system could indeed become uninteresting if:

1. The density of the required energy rate per km^2 is too low,
2. The distribution losses countervail or even wipe out the advantages of polygeneration energy systems.

The first case (point 1) occurs when the buildings are too remote from each other or the energy consumption profiles are too low [103]. In these cases, individual energy systems are more appropriate (especially for the thermal requirements, but in some cases even for the electricity requirements). Figure 1.10 shows by means of an example for heating, how buildings which are remote from all other buildings have their own energy conversion technologies, whereas the buildings having close neighbours are connected to a district energy system.

The aim of the research work described in the present thesis is therefore to develop a method, that helps decision makers and stake-holders define the optimal energy system for districts, for retrofit actions as well as for new districts. To define an *optimal* system, two objectives shall be taken into account by the method, namely

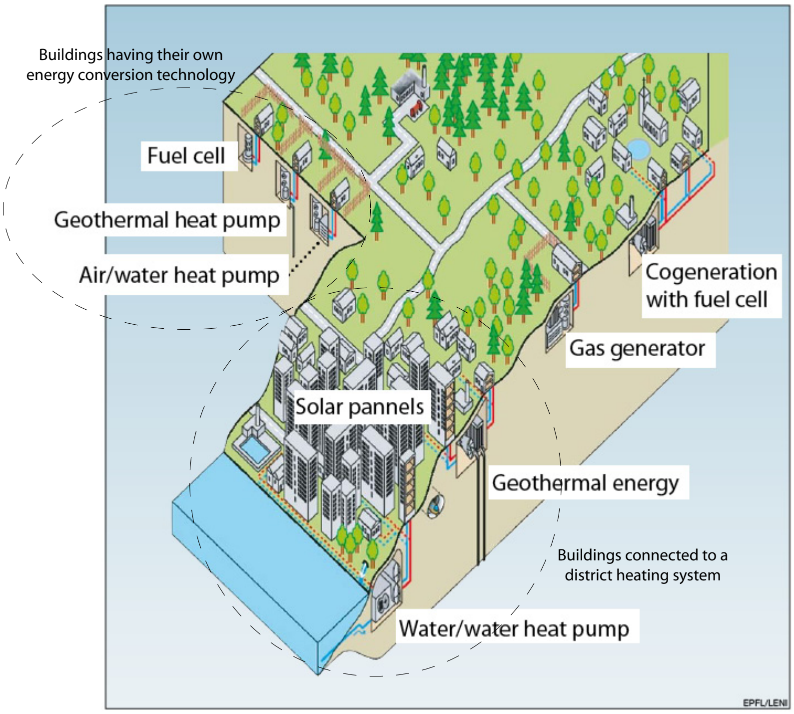

Figure 1.10: District energy system (after [17])

the yearly CO_2 emissions and the yearly costs. This method shall link up the distinctive characteristics of the district for which an energy system needs to be defined, with the different technically feasible solutions, thus considering the minimization of yearly CO_2 emissions and yearly costs as the two objectives. This method will help to optimize the *configuration* (type of energy conversion technologies and distribution network), the *design* (size of the energy conversion technologies) and the *operation strategy* of district energy systems whenever such systems are found to be optimal. The method will also enable the computation of configurations including only individual energy conversion technologies (whenever the energy density is too low for a district energy system to be justified) or a combination of both district and individual energy systems as shown on Figure 1.10. The method will be a tool to perform the following tasks:

- structure the information/data of the analysed district, which is relevant to design and optimize the way the energy services will be provided,
- bring to light the different technological opportunities allowing to meet the requirements of the consumers, taking into account:
  - the energy requirements,
  - the temperature levels at which the energy requirements are requested,
  - the renewable energy sources available,

  - the different types and sizes of energy conversion technologies (including district and individual energy conversion technologies),
  - the different solutions for the design of the distribution network,
  - the synergies between consumers (for instance if one building needs to be cooled down and another to be heaten up, an energy exchange can take place),

- define the optimal configuration for the network and the energy conversion technologies, as well as the optimal operating strategy of the energy conversion technologies,

- define appropriate criteria to discuss the different configurations computed (since there are two objectives, the result of the optimization will not be just one single optimal configurations, and criteria will be needed to discuss the different configurations and choose one).

Briefly said, the method will help determining if, for a given selected district or region, a district energy system is appropriate, and, if yes, it will help answering the following questions:

- Which type and size of energy conversion technologies shall be implemented in the district?
- Where in the district should these technologies be implemented?
- How should the distribution network look like?
- Which operating strategy is to be followed?

The method shall primarily be a design tool and is *not* intended to take over any controlling functions. This will justify the use of rough energy consumption profiles and simplified technology models. However, if controlling aspects shall be included, the method, which shall be developed in a modular way, can be easily adapted (by using detailed consumption profiles and energy conversion technology models).

To develop the method, software tools will be involved (simulation of the energy conversion technologies, simulation of the network, single- and multi-objective optimization). The method is validated based on case studies thank to the collaboration with several partners (Service Cantonal de l'Energie du Canton de Genève and Centre de Recherches Energétiques et Municipales in Martigny).

1.8 Prior art

District energy systems have already been widely studied, and continue to be the object of much interest among researchers. The literature on district energy systems however mainly concerns systems that provide heating, hot water and electricity. The integration of the cooling demands has not yet been extensively studied at the district level. Besides, the majority of the literature on district energy systems concerns the optimization (mainly in terms of costs) of the operation strategies of the energy conversion technologies, and/or the thermo-economic design and optimization of the energy conversion technologies. The literature review can be divided in four main parts regarding the field of interest, namely the effectiveness of a distribution network, the network layout, the technologies, and the mathematical resolution strategies that can be used to develop such a method[15].

1. EFFECTIVENESS OF A DISTRIBUTION NETWORK
   As previously mentioned, if the energy density of a district is too low, district energy systems are not effective solutions, both in terms of emissions and in terms of costs. Yamaguchi et al. [102], as well as Yildirim et al. [103], studied the effectiveness of a district energy system for two different cases, the first one for two closely located buildings in Ōsaka (Japan) and the second one for a university campus in Izmir (Turkey). Yamaguchi considered polygeneration systems to provide heating, cooling and electricity, whereas Yildirim considered only heating. Both studies focus on the phasing of the energy conversion technologies with the requirements of the buildings and do not take into account the design of the network. Due to their very local, case specific, nature, though interesting, and demonstrating the effectiveness of implementing district energy systems for their respective cases, these two studies could not be further used.

2. NETWORK CONFIGURATION
   It is noteworthy that very few papers deal with the issue of the network configuration. One reason for the researchers not to be more interested in this topic could be the belief by some of them that the design of the distribution network is anyway solved by politicians and urban planners, without involving any quantitative support [1], and that it is therefore useless to include the design of the distribution network when studying the thermo-environomic optimization of district energy systems. However, it is the belief of this author that politicians and urban planners could be interested in using quantitative support, if they had the tools to do so [38]. Besides, as already mentioned, district energy systems can show to be inefficient when the required energy density is too low. However, no papers could be found that compute the optimal energy system for a district by comparing district energy systems versus individual energy systems.

   Söderman [86] has studied the network configuration of distributed energy systems and developed a tool for decision makers to design, among others, the layout of the network. However the study does not take into account the temperature levels at which the energy services have to be delivered, although

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[15] As will be explained in Chapter 3, the tool developed in the present thesis results in a Mixed Integer Non Linear Programming problem, for which a resolution strategy needs to be developed.

the temperature level has a major influence when it comes to consider the use of heat pumps or the computation of heat losses. Besides, Söderman does not consider the possibility of excluding a building (included in the district) from the distribution network, if for instance this building was too far away from the rest of the buildings to justify a connection. To compute the network, Söderman uses a mixed integer linear approach. This approach will also be extensively used in the present thesis.

Regarding the optimization of *existing* networks, Benonysson et al. [5] studied the influence of the supply temperature of heating networks on the total operating costs. To perform their study they developed a dynamic model. If the importance of defining an appropriate distribution temperature, as mentioned in the paper, will also be an issue in the present thesis, the use of dynamic modelling techniques will not be further investigated. Such techniques would not be appropriate at the design and optimization levels considered in the present thesis (even though an operation optimization is carried out). Heat losses in networks have also been studied by other researchers like Comakli [21] for instance, without any specific methodological development though.

At the Swiss Federal Institute of Technology in Lausanne, Peng [74] developed a method for the design and thermo-economic optimization for the operation and extension strategy of a district heating network. In his approach, he does not consider aspects such as polygeneration or the integration of multiple energy sources, but part of the theory underlying his algorithm to define the basic meshes that will be taken up in the optimization of the layout of the network, has been considered in the present work.

3. The technologies

   Unlike for the design of the distribution network, the literature on the thermo-economic optimization of district energy conversion technologies connected to a distribution network has been paid much more interest by the researchers. The list of works cited here cannot be considered exhaustive, but gives an overview of the research conducted in this field.

   Von Spakovsky et al. [96]-[97] used mixed integer linear programming models to study the optimization of the operation of the heating and electricity plant connected to the distribution network of the Swiss Federal Institute of Technology in Lausanne (Switzerland), comprising two gas turbines and two heat pumps as well as two storage devices. Rolfsman [78] studied the optimal operation strategy of a combined heat-and-power plant, maximising the production of electricity when it can be sold at peak prices, thus implementing heat storage devices to have enough heat for the district heating system when electricity prices are low and the heat-and-power plant is not running at its maximum load. Rydstrand et al. [80] examined the performance of humidified gas turbine cycles in district heating applications and came to the conclusion that such cycles have a potential to give much lower specific investment costs compared to combined cycles. Hepbasli [51] dealt with the thermodynamic analysis of ground-source heat pump systems for district heating systems in

Turkey, thus showing which elements in the system were responsible for the biggest exergetic losses (namely the compressor and the evaporator of the heat pump), and gave some hints to decision makers to design such a system. Ozgener et al. [72] studied the performance of geothermal district heating systems in Turkey, by comparing the efficiencies of two different sites.

The work conducted in the present thesis goes beyond the above mentioned studies in the sense that the optimization of the energy conversion technologies will not be limited to already existing cases ([96, 97, 78, 51, 72]), or to a single type of technology [80], but will include the optimal choice of the technologies.

At the Swiss Federal Institute of Technology in Lausanne, the theses by Curti [26] and Bürer [12] have to be mentioned at this stage. Curti developed a method to design and optimize district heating systems, following an environomic approach (economic, energetic and environmental). Like Peng, Curti only takes into account heating requirements. However, to meet these requirements, Curti considers cogeneration units. In his method, Curti optimizes one single objective, namely the costs, but accounts for the emissions by using penalty factors that he defines so as to consider not only the emissions of the pollutants, but also their immissions on a local and global scale. Bürer, on the other side, conducted some research work on the potential of polygeneration energy systems to reduce the CO_2 emissions linked to the residential and commercial sectors in Tōkyō and Beijing, based on a mutli-criteria optimization method. Unlike Peng and Curti, Bürer takes into account all the different energy services. In his thesis two very specific case studies bringing into play only a very small size distribution network linking only a few buildings are analysed. He shows that multi-criteria optimization based on advanced evolutionary algorithms can be of great interest to analyse the trade-offs of complex integrated energy systems, between economic and environmental aspects.

The works by Curti and Bürer have been used in the present thesis as starting point.

4. Mathematical resolution strategy
   The decomposition of complex problems including the design and operation of energy systems has been extensively studied by Grossmann and Biegler [6, 49]. The mathematical resolution strategy resulting from of these works, as well as the methodology developed in [99] are taken up in the present thesis. Another methodology, developed by Friedler et al., who studied process synthesis and optimization for the chemical industry [42, 43] also showed very promising results. However, in this methodology, Friedler et al. do not take into account any spatial constraints regarding the location of the technologies. Besides, the chemical processes that are designed are of the continuous type, whereas district energy systems are more related to a batch type operating mode (the energy requirements vary from one period to the other).

1.9 Conclusion

In this chapter the motivation for the present thesis, namely the development of a tool to design and optimize district energy systems, has been presented. The first part of the chapter dealt with the notion of sustainability and the Kyoto protocol, which assesses the relation between climate change and greenhouse gas emissions. It was then shown that in Switzerland there are mainly two sectors which have to be addressed when dealing with the reduction of greenhouse gas emissions: heating and transportation. However, dealing with heating requires to take into account also other energy services such as cooling and electricity, in order not to overlook energetically interesting solutions such as polygeneration energy conversion technologies. Because such systems are not suitable in single buildings, distribution networks need to be designed to connect several buildings together. The resulting system including the energy conversion technologies and the distribution network is called *district energy system*. Since no method presently exists to design and optimize such systems, the chapter ended explaining the needs for such a tool[16] to be developed.

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[16] The words *method* and *tool* are used interchangeably in this thesis.

Chapter 2

Method for the design and optimization of district energy systems

2.1 Introduction

In this chapter, the main parts of the method developed to design and optimize district energy systems, hereafter DESD(OP)^2 (District Energy System Design and OPeration OPtimization), that has been introduced in the last part of Chapter 1 shall be explained. The method is depicted in Figure 2.1. It basically comprises three phases: a *Structuring* phase, an *Optimization* phase and a *Post-processing* phase. The remainder of this chapter will be organized following Figure 2.1, with the description of the three phases. Since the structuring and the post-processing phases are fairly straightforward, they will be treated rather briefly. The optimization phase, on the contrary, is the core of the present thesis and will therefore be explained in greater details in two separate chapters (Chapters 3 and 4).

2.2 Structuring phase

The structuring phase is the phase in which all the relevant information regarding the district for which an energy system needs to be designed, are gathered, structured, and put in the required form to be used in the optimization phase. The structuring phase is the first step directly following the delimitation of the district or region of interest. If the types of information required to design and optimize the district energy system remain the same regardless of the location of the district analysed, the content of these different inputs will vary greatly with the location of the district.

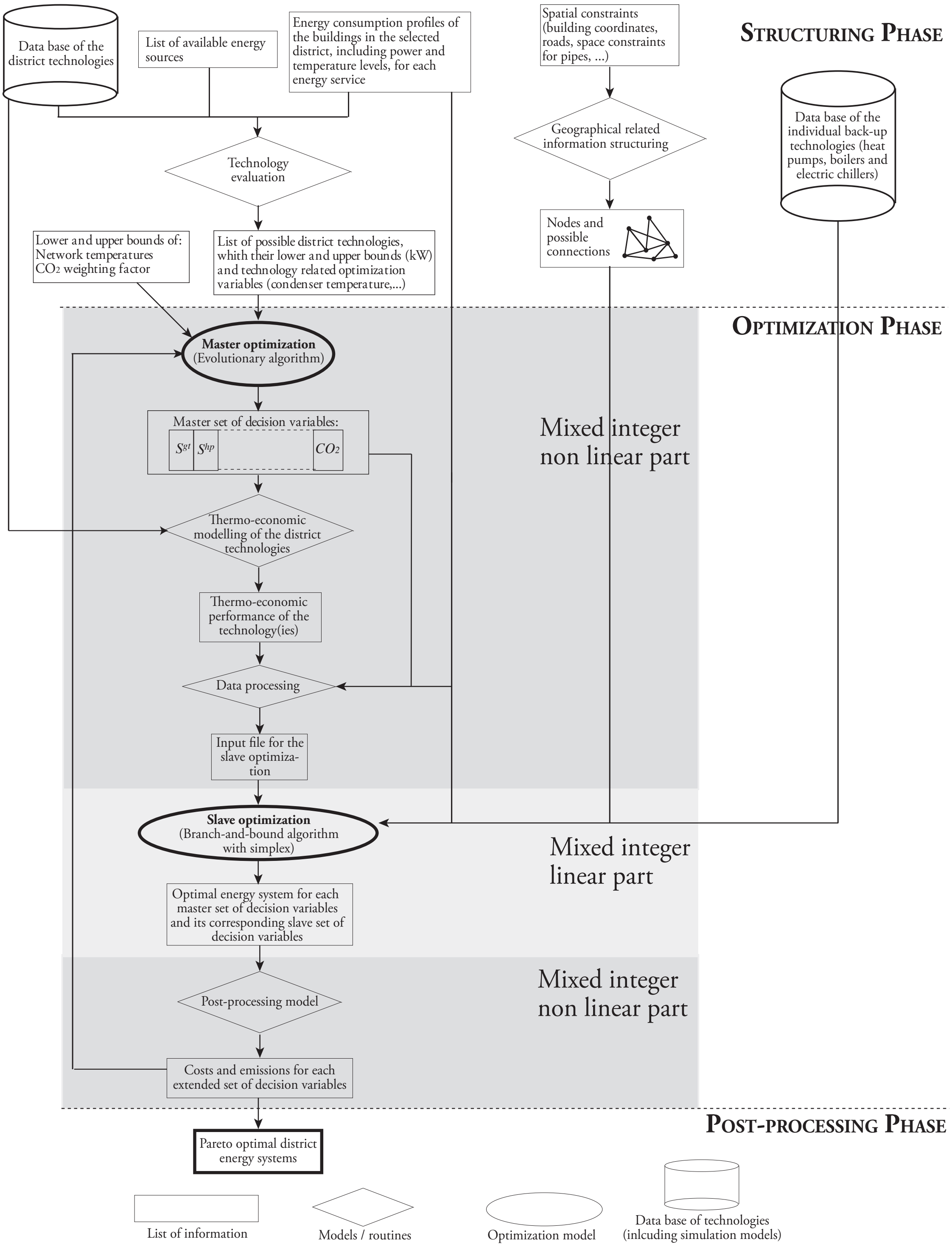

Figure 2.1: Method developed to solve the district energy system design and operation problem

These types are:

1. THE LIST OF AVAILABLE ENERGY SOURCES
   A comprehensive analysis and listing of the available energy sources in the district that can be used for the *district* energy conversion technologies has to be performed. These include natural gas and renewable energy sources such as wind, waste, sewage water, lakes, rivers, sun, geothermal energy,... For each energy source, all the characteristic parameters such as for instance the temperature for a lake, the velocity for wind, the temperature and the maximum recoverable energy for sewage water,.... have to be included in the analysis. Heating oil is deliberately not considered at this stage, since in Switzerland heating oil is mainly used for individual boilers, which have been categorised as individual back-up devices and do not belong to the district technologies.

2. ENERGY CONSUMPTION PROFILES INCLUDING POWER AND TEMPERATURE LEVELS
   The energy consumption profiles for the different energy services need to be known in order to compute the optimal design and operation of the district energy system. For the thermal energy requirements (heating, hot water and cooling) it is important not only to know the amount of energy required, but also the *temperature level* at which this energy needs to be provided. Besides, for all energy services the *power level* is of utmost importance to design the size of the energy conversion technologies. Therefore, the profiles of the energy requirements, for *all* energy services, are best given in average hourly rates for each period (in kW), together with the duration of each period in hours. Usually, these profiles are not only difficult to obtain (especially for the temperature levels), they also contain large uncertainties due to their stochastic nature. Besides, for cooling, there is not yet enough data available from previous years, to make reasonable statistics. In Chapter 6 it is shown how such data can be computed when they are missing, drawing on building models as well as on geographical information systems. It is noteworthy at this stage, that since the goal of the DESD(OP)^2 problem is not to perform any precise hour by hour controlling or regulation, it is useless to use hour by hour profiles for the whole year. This would add an unnecessary level of details that would drastically increase the resolution time. In many cases, a six period profile including a day and a night period for summer, winter and mid-season, can already be considered sufficient. Figure 2.2 shows such an energy consumption profile.

   Beside these two first types of information that will help defining appropriate energy conversion technologies to meet the requirements of the district, there is the *data base of district technologies. District* technologies are the energy conversion technologies that *are connected* to the distribution networks and provide heating, hot water, cooling and electricity to the different customers

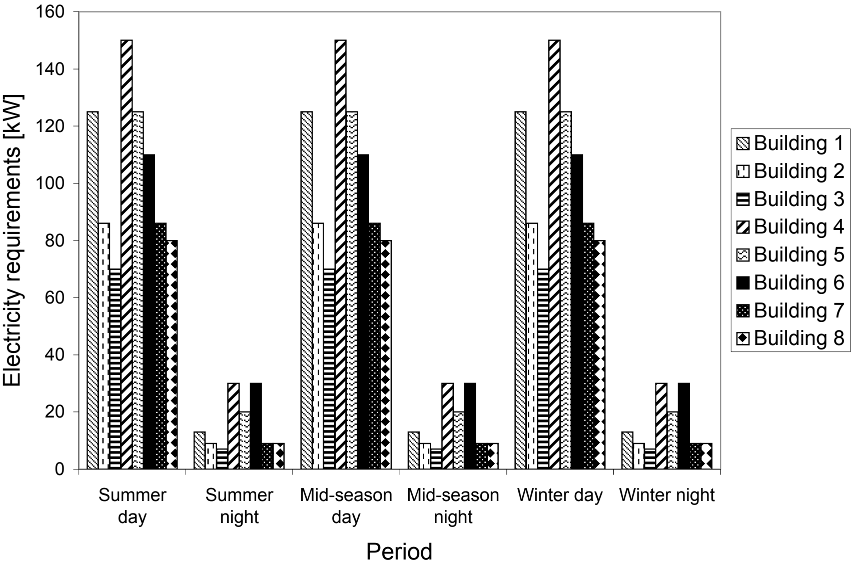

Figure 2.2: Electricity requirements profile including 6 periods for the whole year

in the district via these networks[1]. The district technologies are the one that will be implemented in the energy plant from which the distribution networks will depart. A data base, including the thermo-economic simulation models of the different possible district energy conversion technologies, is set up. It includes among others heat pumps, gas engines, gas turbines combined cycles, windmills, photovoltaic cells,... . Should a technology, that is considered promising for the analysed district, be missing in the data base, it has to be added and thereby contribute to the general enrichment of the data base.
The content of the data base of district energy conversion technologies, like the content of the data base of individual back-up energy conversion technologies explained further down this section, is indeed not depend on the district analysed.

The list of available energy sources and the energy consumption profiles (including the temperature and power levels) are evaluated and compared with the content of the data base of district technologies, in the *Technology evaluation* tool. The goal is to establish a list of district technologies that can be used in the analysed district. Unlike the data base of the district technologies, this list is specific to the district. For instance, if the district is located in the vicinity of a lake or a river, heat pumps will be an essential element of the list of district technologies. Besides, if geothermal energy is available, a steam turbine or an organic Rankine cycle can be implemented. On the other hand, considering wind mills in a city like Geneva to produce

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[1] These technologies should not be mistaken with the individual back-up technologies (further down this section), that are not connected to the distribution networks

electricity, will not lead to a reasonable solution, due to the unfavourable wind conditions in Geneva. Wind mills would therefore not appear in the list for a district located in Geneva. Or else, if the maximum average hourly electricity rate amounts to 4 000 kW for instance, no gas turbine combined cycle will be selected (too small requirements for such a technology).

The last type of required information is the:

3. Spatial (geographical) constraints
In many cases (for instance in retrofits), the district energy system has to fit in an existing district. Therefore constraints such as the coordinates of the buildings, the layout of the roads, space constraints in existing underground channels,... have to be taken into account when computing possible configurations of the district energy system, especially for the network layout. Typically, a pipe will for instance not be allowed to follow the shortest path between two buildings, as this path might go right across another building. There are certain geographical routes that have to be followed, as shown in Figure 2.3. Usually, this type of information will not be readily available and usable by the design and optimization algorithm. A geographical related information structuring procedure needs to be undertaken to put this information in an appropriate form that can be used in the optimization phase. This procedure results in a list of nodes, possible connections and their related space constraints (maximum possible diameter to fit in the underground channel for instance).

Finally, the last element which will be needed is the data base of the individual back-up technologies. Beside the *district* energy conversion technologies, there are also some *individual* back-up technologies available. The individual technologies are implemented directly in the building they serve, in case the district energy system cannot meet the energy requirements of this building (for instance if the temperature level at which the heat is required by a single given building is above the temperature level of the network, or if the building is located too far away from the rest of the buildings to justify a connection). These individual technologies are considered back-up technologies [30, 29]. The list of possible back-up technologies includes[2]:

- Heating and hot water:
    - Water/water heat-pumps
    - Air/water heat-pumps
    - Boilers
- Cooling
    - Electric chillers

Note that unlike the choice of the district energy conversion technologies, the choice of the types of back-up technologies has not been made location dependent. The

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[2] For electricity, the back-up is the grid.

data base of back-up technologies can be enriched at any time, for instance by adding advanced air/water heat pumps taking advantage of the exhaust air of the buildings [81].

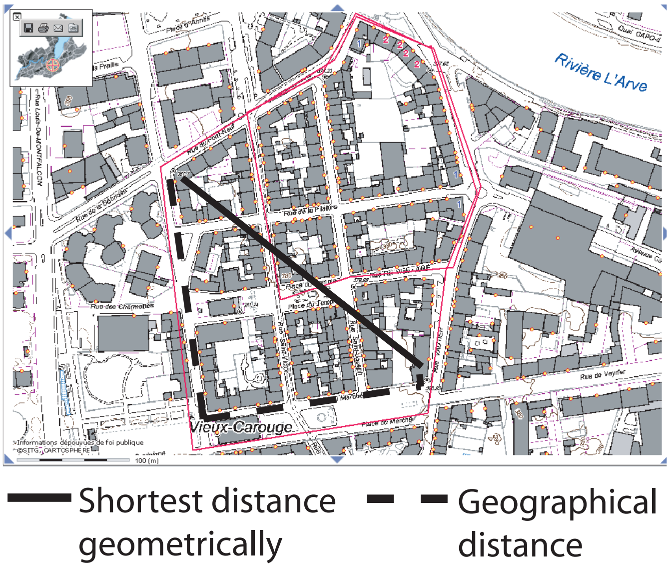

Figure 2.3: Difference between the geographical route that has to be followed to connect two buildings, and the shortest distance geometrically [98]

Figure 2.4 shows an example of a district with the consumption profiles given for three buildings. This virtual district has been imagined on purpose to develop the method, and will be used in Chapter 5 to demonstrate the method. It is characterized by a certain number of buildings including their consumption profiles, by roads connecting the buildings (dashed lines), and by obstacles (lakes for instance as shown on Figure 2.4, but also large rivers, protected zones,...) forbidding the direct connection of two buildings.

2.3 Optimization phase

Once the required information have been appropriately processed into usable inputs for the optimization phase, the optimization phase of the DESD(OP)^2 problem can be started. The DESD(OP)^2 problem is a *multi-objective* optimization problem having the yearly CO_2 emissions and costs as its two objectives. Because the optimization of the DESD(OP)^2 problem is a *multi-objective* optimization, the result will not be a unique solution, but a collection of solutions. Graphically, the result of a multi-objective optimization is represented in a so-called Pareto frontier, as the one shown on Figure 3.2 and explained in the corresponding section. The goal of the optimization phase is therefore to generate the solutions belonging to this Pareto frontier, by optimizing the following decision variables:

1. District energy conversion technologies:
    - Type
    - Design size
    - Location in the network
    - Technology related parameters if necessary (like for instance the condenser and evaporator temperatures of a heat pumps if any)
    - Operation strategy
2. Network:
    - Layout of the pipes
    - Supply and return temperatures of the distribution networks (heating and cooling)
    - Flows in the pipes (mass, energy and power)
3. Individual back-up energy conversion technologies:
    - Type
    - Design size
    - Location in the network
    - Operation strategy

The design and optimization of such a district energy system is complex for several reasons:

1. District energy systems combine spatial (location of the buildings) and temporal (consumption profiles) aspects.
2. The consumption profiles of the different energy services vary during the day, and from one day to the other, in a stochastic manner. Because of these stochastic variations, the problem becomes a multi-period problem, which is much more complex than if the requirements remained unchanged with respect to time, or changed in a deterministic way.
3. The temperature level at which a building requires heating or cooling needs to be considered. Since this temperature level can vary from building to building, and even from period to period for a same building, the problem cannot be solved by solving only first principle energy balances. Process integration aspects have to be considered.
4. The number of the various combinations of different locations and sizes of energy conversion technologies is high (district as well as individual back-up technologies).
5. The number of security and spatial constraints due to already existing equipment (for instance a technical gallery in which wires for telecommunication are implemented) is usually large in a city.

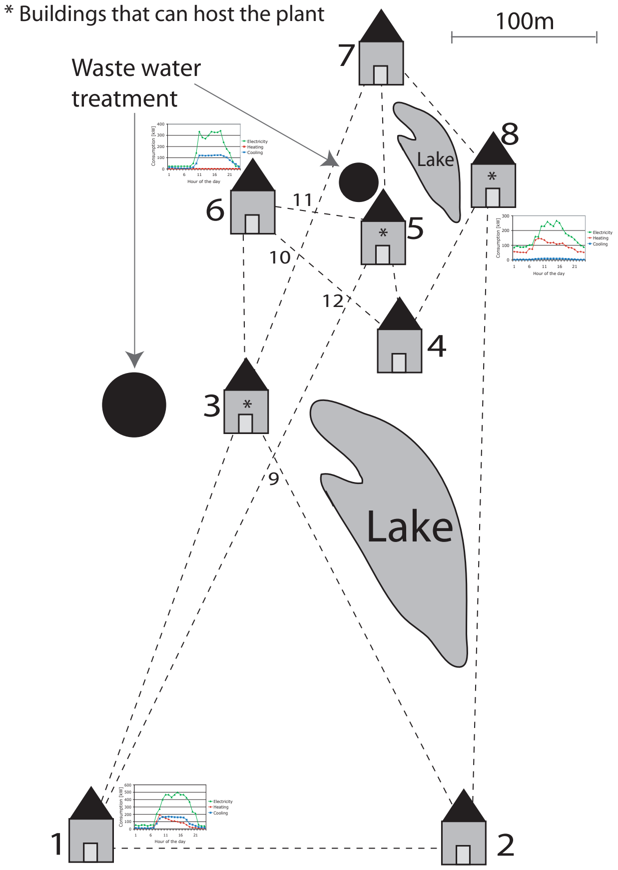

Figure 2.4: Example district used to develop the network design and optimization algorithm

Due to the complexity of the problem and the large number of decision variables involved[3], the optimization phase is decomposed in a master optimization and a slave optimization, both parts optimizing different decision variables. The decomposition that was already successfully implemented in the study mentioned in Section 1.6 on the optimal design and operation management of an SOFC-based energy system for a building [99], is taken up and further developed. It will be explained in greater details in Chapter 3. Basically, a master optimizer computes a so-called *master set* of decision variables, including decision variables related to the choice and design of the district energy conversion technologies, as well as the supply and return temperatures of the networks (heating and cooling). The decision variables, which are directly linked to the type and size of the district technologies, are given as inputs to the corresponding thermo-economic models included in the data base, to compute the performances of the technologies (efficiencies, mass flow rates,...) and investment costs. The performances, together with further decision variables of the master set (network temperatures), as well as the consumption profiles, are processed in order

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[3] As will be shown in Chapter 5, the number of decision variables can easily amount up to 50'000 variables.

to be usable by the slave optimizer. This processing is explained in Section 4.5. The result of this processing, together with the outputs from the geographical related information structuring process, the energy consumption profiles, and the models of the individual back-up energy conversion technologies, are passed over to the slave optimizer. The slave optimizer computes the *slave set* of decision variables, given the master set of decision variables, namely the layout and operation of the network, and the location and operation of the district as well as individual back-up energy conversion technologies. This whole optimization process is run iteratively until convergence is reached. In other words, the iterative process is stopped when no further improvement is gained from new iterations.

2.4 The post-processing phase

In the post-processing phase, the Pareto optimal frontier with the different solutions is evaluated. To perform this evaluation and choose the solution that will finally be implemented, decision-makers rely on a list of criteria, such as for instance:

- the weight to give to each objective,
- the available budget,
- the CO_2 emissions reduction targets according to the Kyoto protocol,
- the result of the sensitivity analysis on some parameters,
- the acceptance of the population for given solutions,
- the implementation delays,
- ...

The success of this phase strongly relies on a close collaboration between all the decision-makers, stake-holders and engineers.

2.5 Conclusion

In this chapter the method developed to solve the DESD(OP)^2 problem is pictured. The DESD(OP)^2 problem is solved by means of a multi-objective optimization procedure, optimizing both yearly CO_2 emissions and costs, and resulting in a Pareto optimal frontier that needs to be evaluated. The method includes three phases: a structuring phase, an optimization phase and a post-processing phase, or, according to Maréchal [64], the method applies the *AGE*-principle:

> Analyse the problem, Generate solutions, Evaluate the solutions.

Chapter 3

Solution strategy of the optimization phase

3.1 Introduction

In this chapter, the optimization strategy developed to solve the optimization phase of the method described in the previous chapter, is explained in detail. Even though many optimization algorithms exist to solve various types of problems, none of them can pretend of solving the DESD(OP)^2 problem straight ahead. There are two main reasons for this. The first reason is that, in addition to being a Mixed Integer Non Linear Programming problem (as will be shown), and thus belonging to the most complex class of optimization problems, the DESD(OP)^2 problem is a *bi-level* problem (design level and operational level). The second, and most important reason, is that the DESD(OP)^2 problem is a *multi-objective* optimization problem, and not many algorithms exist that can handle more than one objective at the time. In order to be able to solve the DESD(OP)^2 problem, a strategy has therefore been developed that combines different optimization algorithms. In this chapter, this *strategy* is explained in details, showing how different existing types of optimization algorithms have been combined, taking to account the advantages of each of them.

3.2 Mathematical structure of the DESD(OP)^2 optimization problem

In order to define an effective resolution strategy to solve the DESD(OP)^2 problem, calling on the appropriate tools, one has to analyse the mathematical structure of the problem: linearity, type of variables[1] and number of objectives. LINEARITY Looking back at Figure 2.1, one can see that in the optimization phase, models of energy conversion technologies are required. Besides, if it has not been pictured yet

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[1] integer or continuous

how pressure or heat losses will be be accounted for, it seems obvious that such parameters will have some importance when designing the heating or cooling distribution networks. According to thermodynamics, the computing of these latter parameters, as well as the models for the energy conversion technologies are not linear. The DESD(OP)^2 problem therefore belongs to the class of non linear problems. Note that if some variables can be linearized with a few reasonably posed assumptions (see Section 4.5), for others it is not possible. The reason for this does not lie in the sole loss of precision that is linked with any linearization and that can lead to bad results. It also lies in the fact that the tool to solve the DESD(OP)^2 optimization problem is best developed in a very modular way, allowing, for instance, the implementation of energy conversion technology models from different authors. Such models cannot be linearized without losing all the expertise of its author(s), which would be counterproductive since this expertise is precisely what is sought for.

TYPE OF VARIABLES
The DESD(OP)^2 problem includes continuous as well as integer type variables. Variables are indeed required to define, for instance, on which node in the district the technologies are best implemented, or how to connect the buildings. For these purposes, integer variables are required. Consequently, the DESD(OP)^2 problem belongs to the class of the *Mixed Integer Non Linear Programming optimization problems* (MINLP).

NUMBER OF OBJECTIVES
It is important to stress, once again, the multi-objective character of the problem. This is an important issue, since the majority of the optimization algorithms are single objective algorithms. When dealing with multi-objective problems, these algorithms use weighting factors for the different objectives in order to combine the different objectives into a single objective. Another technique often used is to add constraints to the problem to represent the objectives that are not considered directly in the objective function. For the DESD(OP)^2 optimization problem, even if such techniques could not be completely avoided, as explained in Paragraph 3.4.4, they were nonetheless restricted to a certain sub-problem of the overall DESD(OP)^2 problem, and were avoided for the rest of the problem. The reason for this is to avoid as much as possible to influence the solution by arbitrarily set weights or constraints.

The general formulation of a multi-objective MINLP optimization problem is (after [39]):

$$\min Z_1, Z_2 = f(x,y) \text{ s.t. } \begin{cases} h(x,y) = 0 \\ g(x,y) \leq 0 \\ x \in X, y \in Y \end{cases}$$

with $X \in \mathbb{R}^n$ being the vector of continuous variables and $Y \in \mathbb{R}^m$ the vector of integer variables. f is a function $\mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$, h a function $\mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^p$, and g a function $\mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^q$. Note that in the DESD(OP)^2 problem, since the integer variables are used to define the implementation or not of a piece of equipment or a connection, they are restricted to take 0-1 values, and are called hereafter binary variables. Looking at Table 3.1, that resumes the most common optimization methods for the different types of problems[2], several methods exist to solve MINLP optimization problems[3]. Beside the type of problem for which optimization methods are appropriate, the method can be further classified in deterministic and stochastic methods. A deterministic method always follows the same path to find the optimum, whereas for stochastic methods, different paths will be followed for a same optimization problem (and the same starting point) from one optimization run to another. This is due to the fact that stochastic problems involve search strategies that are characterized by randomness.

Let us analyse now how/if the existing optimization algorithms for MINLP problems can be used to solve the DESD(OP)^2 problem.

3.3 MINLP (Mixed Integer Non Linear Programming) optimization algorithms

3.3.1 Deterministic optimization methods

Deterministic methods for solving MINLP problems are based on a decomposition of the problem. The purpose of decomposing a MINLP problem is to break down a difficult problem into several easier ones to solve smaller problems, thus enabling the use of known tools and, usually, a significant decrease of the solution time. Following the decomposition strategy, deterministic methods can again be divided into two categories. The first category comprises the methods that make use of the mathematical structure of the MINLP optimization problem to decompose it, whereas the second category focuses on the hierarchical structure of the MINLP problem for the decomposition [49].

METHODS BASED ON THE MATHEMATICAL STRUCTURE
The methods based on the mathematical structure basically consider the fact that there are two types of variables to optimize (continuous and binary variables), to decompose the problem. These methods include for instance [6] the *Generalized Benders Decomposition* algorithm (GBD, proposed by Benders in 1962 [4] and generalized by Geoffrion in 1972), or the *Outer-Approximation* algorithm (OA, first proposed by Duran and Grossmann in 1986 [33]). The GBD and the OA algorithms exploit the mathematical structure of the problem to decompose it in a Non Linear Part (called NLP subproblem) and a mixed integer linear part (called MILP mas-

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[2] The enumeration is far from being exhaustive!

[3] Note that if by misuse of language the methods of Table 3.1 are often referred to as *algorithms*, strictly spoken an algorithm is a method that, when followed step by step, finds the optimum with 100% certainty. All the other methods, for which the optimality of a solution cannot be proven, are de facto *heuristics* [8]. Following this definition, the evolutionary algorithm for instance, which is mentioned in the table, is in fact a heuristic and not an algorithm.

Optimization problem type	Deterministic methods	Stochastic methods
LP	Simplex method	
	Interior point method	
IP		Branch-and-bound
MILP		Branch-and-bound combined with the Simplex or the interior point method
	Generalized Bender's Decomposition	
	Outer-approximation	
	Bi-level decomposition method	
NLP	Reduced gradient method	Evolutionary algorithm
	Successive quadratic programming method	
		Simulated annealing
MINLP	Generalized Bender's Decomposition	Evolutionary algorithm
	Outer-approximation	Simulated annealing
	Bi-level decomposition method	

Table 3.1: Types of optimization problems and common resolution algorithms, LP: Linear Programming, IP: Integer Programming, MILP: Mixed Integer Programming, NLP: Non Linear Programming, MINLP: Mixed Integer Non Linear Programming [82, 49, 6, 31, 39]

ter problem). GBD and OA solve the optimization in an iterative process. The non linear part optimizes the continuous variables and provides an upper bound to the optimization problem, whereas the mixed integer linear part provides values for the integer variables as well as a lower bound to the optimization problem. Both parts are solved iteratively, and the optimum of the MINLP optimization problem is reached when the upper bound is smaller or equal to the lower bound [31]. The major difference between both algorithms is that in the GBD algorithm the MILP master problem is based on the Lagrangian representation of the NLP subproblem, whereas in the OA algorithm the MILP master problem is based on a Taylor series expansion of the original MINLP problem [31].

Two major drawbacks are linked with these methods. The first one is that they require the objective function and the constraints to be *convex* [49], as well as the set of decision variables X. A set X is convex if, for any two vectors x_1 and x_2 in X, the vector $x = \lambda x_1 + (1-\lambda)x_2 \ \forall \lambda \in [0,1]$ is also included in X. A function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is convex, if for all x_1, $x_2 \in X$, and $y_1 \in Y$ fixed (Y being the set of binary variables), following inequality holds [7]:

$$f((\lambda x_1 + (1-\lambda)x_2), y_1) \leq \lambda f(x_1, y_1) + (1-\lambda) f(x_2, y_1) \qquad \forall \lambda \in [0,1]$$

Even if the development for nonconvex continuous optimization has received considerable attention in the literature (see [49] for example), the implementation of these methods remain cumbersome for a problem in which the formulation of the constraints keeps changing (different districts, different energy conversion technology models,...). The second drawback is that these methods have been developed for single objective MINLP problems, and, to the best knowledge of the author, they have not yet been adapted to *multi*-objective optimization problems.

OPTIMIZATION METHODS INVOLVING A DECOMPOSITION BASED ON THE HIERARCHICAL STRUCTURE

On the other hand, instead of considering the mathematical structure of the problem, one can exploit the hierarchical structure of the problem. The DESD(OP)^2 optimization problem is a problem with two distinct parts: a design part and an operation part. Such problems can be solved using what Iyer and Grossmann call the *bi-level* decomposition [57]. As stated by the authors in the referenced paper, one approach to exploit the hierarchical structure of combined design, planning and/or scheduling models is to decompose the model into an upper level problem at the higher hierarchical level (in which the optimized variables are mainly design decision variables), and a lower level problem at a lower hierarchical level (in which the optimized variables are mainly operation decision variables). Iyer and Grossmann have proposed this bi-level decomposition in 1998 for MILP problems. The method was expanded later (2000) by Van der Heever and Grossmann to also decompose MINLP problems [93].

Like for the methods based on a decomposition following the mathematical structure, the problem initially needed to be convex to use this method. Horst et al. [54] suggested the use of convex envelopes when dealing with non convex problems. Convex envelopes represent convex underestimator of the function to minimize.

However, with the use of convex envelopes, the global optimum cannot be guaranteed anymore. Besides, like the decomposition method based on the mathematical structure of the problem, the bi-level decomposition has been developed for single-objective optimization problems.

Conclusion regarding deterministic methods

Unfortunately, the use of deterministic optimization algorithms to solve the DESD(OP)^2 optimization problem appeared to be inappropriate for the following reasons:

1. In the case of the DESD(OP)^2 problem, the characteristics of the analysed district change from case to case, requiring the DESD(OP)^2 tool to be modular. Depending on the geographical location of the analysed district for instance, different energy conversion technologies will be looked at for the energy system. The technologies implemented can indeed vary between a district located near a lake and that might implement heat pumps, and a district located in a region in which windmills are an effective and efficient technology. Consequently, different models will be used for the energy conversion technologies for these two districts. Besides, even for a same type of energy conversion technology, different types of models can be used. Some of the models can be simple linear relations, whereas others can be more detailed, non linear, and include many subroutines. The choice of the type of model (simple or detailed) depends on the requested accuracy and/or on the availability of the models. Finally, in the event of using some models of other researchers, the shape of the model will not be known a priori by the person optimizing the district energy system. This liberty of choosing the thermo-economic models that has to be warranted, prevents from ensuring the convexity and the differentiability of the DESD(OP)^2 problem.

2. The deterministic algorithms described are not suited for multi-objective problems. To overcome this issue, one could theoretically fix one of the two objectives as a parameter and define a constraint, while optimizing the other objective. By setting the fixed parameter successively at different (increasing or decreasing) values, and optimizing the function for each value of the parameter, one would get a curve with the trade-offs between both objectives. However this strategy calls for another strategy to fix the parameter at successive reasonable values, which is anything but trivial (definition of the increment, minimum/maximum value of the parameter,...). Besides, with such as strategy the optimization algorithm might find only one solution for each value of the parameter, even in cases where more than one solution exist.

For these reasons, the deterministic methods described so far have not been selected to solve the DESD(OP)^2 problem. However, the *idea* of a decomposition based on mathematical or hierarchical aspects will nonetheless be further taken up to define an appropriate optimization strategy for the DESD(OP)^2 problem.

3.3.2 Stochastic optimization methods

Stochastic optimization methods rely on heuristics to compute an optimal solution. Examples of the most common stochastic optimization methods include the *simulated annealing algorithm* or the *evolutionary algorithm* [49].

SIMULATED ANNEALING ALGORITHM [31]
Simulated annealing is based on ideas from thermodynamics. In physical annealing, all atomic particles arrange themselves in a lattice formation that minimizes the amount of energy in the substance, provided the initial temperature is sufficiently high and the cooling is carried out slowly. A too rapid decrease of the temperature would indeed congeal the system in a state characterized by a big disorder. A slow decrease of the temperature on the contrary allows the system to evolve to a thermal equilibrium. The thermal equilibrium is characterized by the probability P_r of being in a state with energy E given by the Boltzmann distribution:

$$P_r(E) = \exp(-\frac{E}{K_b T})$$

where K_b is Boltzman's constant ($1.3806 \cdot 10^{23}$ J/K).

The simulated annealing algorithm thus consists in starting from a chosen initial configuration for a given system, and to let the system evolve iteratively to further configurations by elementary changes in its configuration, in order to decrease its "energy". If the change in the configuration results in a higher energy level, the change is accepted according to the Metropolis criteria (accepted with probability $P = exp - \frac{\Delta E}{K_b T}$). This implies that at large pseudo-temperatures, a large percentage of uphill changes are accepted. However as the temperature decreases a small percentage of uphill changes are accepted. After the system has evolved to thermal equilibrium at a given pseudo-temperature, the pseudo-temperature is lowered and the annealing process continues until the system reaches a pseudo-temperature that represents "freezing". In the case of the DESD(OP)^2 optimization problem, the energy could be the annual CO_2 emissions or costs, and the temperature a configuration with given energy conversion technologies, distinct connections between nodes,... The major difficulty in the application of simulated annealing is to define the analogs to the entities in physical annealing when performing optimizations. Specifically, it is necessary to specify the following: an initial value for the objective function, the initial and final temperatures, or the equilibrium detection method [31, 74, 20]. These difficulties become even worth when dealing with multi-objective problems like the DESD(OP)^2 problem.

EVOLUTIONARY ALGORITHM [62]
The evolutionary algorithm is based on the same principles as genetic algorithms, namely on the mechanics of natural selection and natural genetics. In order to find the optimal solution, the evolutionary algorithm creates randomly a population of individuals. An individual is a *genome*, characterized by a set of values given for each decision variable. The score, or performance, of each individual is evaluated. New individuals are then created, based on the scores of the existing individuals,

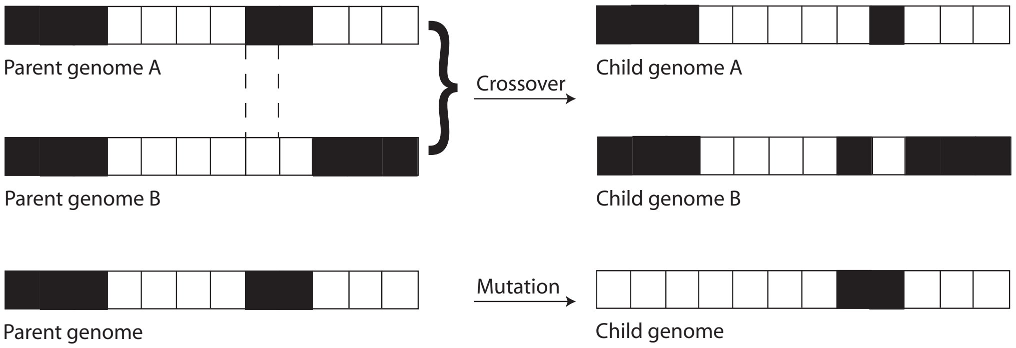

Figure 3.1: Crossover and mutation operations (after [31])

using a set of combination operators such as crossover and mutation (see Figure 3.1) for instance. The crossover operator randomly exchanges parts of the genes of two parent solution strings to generate two child solutions. Mutation is an operator that increases the variability of the population by changing randomly the value of one gene in the genome, corresponding to one decision variable, with a new value included in the permissible range of this decision variable. The evolution process is continued sufficiently, until a given termination criterion is satisfied. Recently, an evolutionary algorithm based Multi-Objective Optimizer (MOO) was developed at the Laboratory of Industrial Energy Systems at the Swiss Federal Institute of Technology in Lausanne [62]. This optimizer computes the trade-offs between multiple objectives for different solutions. This multi-objective strategy results in an estimation of the Pareto optimal frontier (Figure 3.2) that represents the set of optimal points that can be considered to be optimal in terms of one or both of the two objectives. Each point of this curve corresponds to a genome, or set of decision variables[4]. In order to preserve the diversity of the population in the search space of the decision variables and avoid the algorithm from getting trapped in a local optimum, MOO includes a range of tools such as clustering (also called grouping)[5], that ensure the whole search space to be analysed.

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[4] Note that such a Pareto optimal frontier would also result from a serie of single-objective optimizations in which the second objective is represented by a parameter having its value successively changed as explained in the conclusion of Section 3.3.1.

[5] Clustering preserves diversity by dividing the population into clusters in the parameter space, and then letting these clusters evolve somewhat independently - there is no competition between clusters, though there is some interbreeding. [62]

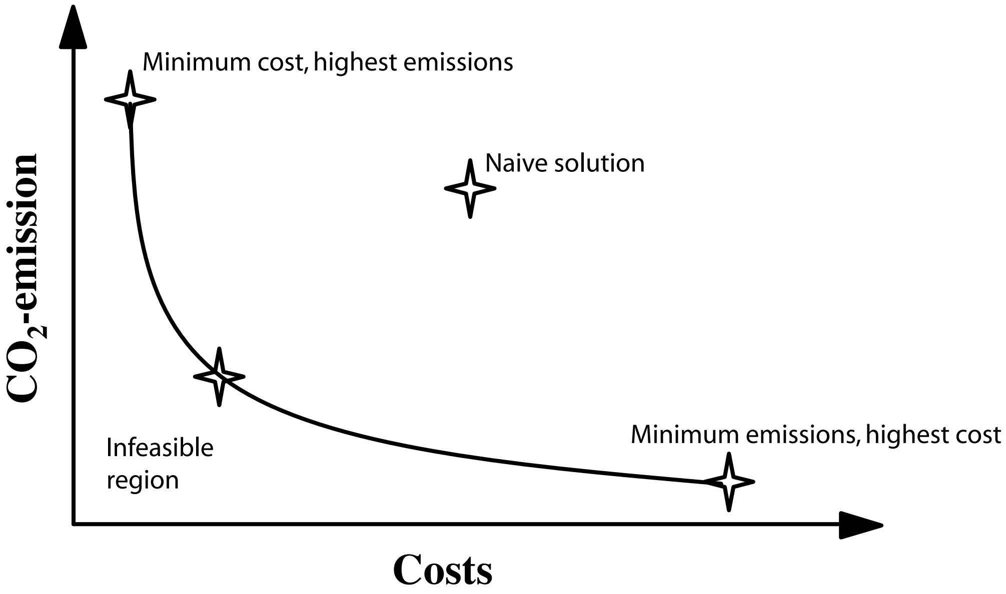

Figure 3.2: Pareto optimal frontier

3.4 Solution strategy implemented in the DESD(OP)^2 problem

3.4.1 Necessity of decomposing the DESD(OP)^2 problem

As already mentioned, the algorithms described in Paragraph 3.3.1 are not suited to solve the DESD(OP)^2 problem since they have mainly been developed for problems which are convex, single objective, and not modular. On the other hand, the simulated annealing algorithm (Paragraph 3.3.2) does not require the problem to be convex, but also has the disadvantage of solving single-objective optimization problems. Finally, the multi-objective evolutionary optimizer MOO has none of the two major drawbacks, since it does not require convexity and is able to handle multi-objective optimization problems. Besides, evolutionary algorithms follow a black-box logic which enables the development of a very modular tool to solve the DESD(OP)^2 problem. However, using only MOO as the optimization tool would be very inefficient considering the large number of decision variables, and the even larger possibilities to combine these variables (especially the binary variables) into non feasible solutions. Let us take, for instance, the decision variable linked to the existence or not of a pipe between two nodes $X_{i,j}$. There are as many $X_{i,j}$ as there are possible connections between nodes. The probability for the evolutionary algorithm to choose a set of $X_{i,j}$ resulting in an unfeasible network (unconnected for instance) is much larger than the probability to choose a set of $X_{i,j}$ resulting in a feasible network. Therefore, the evolutionary algorithm will spend much time calculating unfeasible solutions that will have to be penalized by an appropriate factor (the definition of which is anything but a trivial task). However, thanks to an appropriate resolution strategy of the DESD(OP)^2 problem involving a decomposition of the problem, it will be shown how one can make use of the advantages of a tool like MOO, and still get rid of the above mentioned inconvenience. To develop an appropriate decomposition strategy, the mathematical and bi-level decompositions of the deterministic optimization algorithms are taken up again with respect to the DESD(OP)^2 problem to verify if, and how, they can be useful in the case of the DESD(OP)^2 problem, with a few modifications though.

3.4.2 Mathematical decomposition

Following Grossmann and Biegler [6, 49], the mathematical decomposition separates the overall problem in a sub-problem optimizing the binary variables, and a sub-problem optimizing the continuous variables. In the DESD(OP)^2 problem, the binary variables are related to the choice of the energy conversion technologies, the location or not of an energy conversion technology on a node, or on the connection or not of two nodes. Continuous variables, on the other side, are related to the design size of the energy conversion technologies, the supply and return temperatures of the networks, the operation strategy of the energy conversion technologies, and the flows (power, energy and mass) between the nodes in the network. According to the preceding, the optimization of both the energy conversion technologies and the network imply binary and continuous variables. In other words, decomposing the DESD(OP)^2 problem in a sub-problem optimizing the binary variables, and another sub-problem optimizing the continuous variables, results in two sub-problems, both including decision variables related to the energy conversion technologies *and* to the network. Such a decomposition is not very sensible in the case of the DESD(OP)^2 problem, because it results in two sub-problems for which no optimization tool exists. Keeping in mind that the purpose of decomposing a complex problem, whatever the type of the problem, into two or more sub-problems, is to come down to smaller, easier to solve sub-problems, for which tools already exist, the above mentioned decomposition in binary and continuous decision variables misses the mark. The idea of the mathematical decomposition is nonetheless further taken up, however not to separate continuous from integer variables, but linear from non linear constraints. It's a matter of fact, indeed, that linear optimization algorithms to solve *network* problems have been paid much interest in the last two centuries, and keep being one of the most researched topic in the field of optimization. One of the best known network optimization problem is the so-called Travelling Salesman Problem, which has following statement [82]: Given a number of cities together with the mutual distances (the distance table), the objective is to determine a shortest route along the cities, such that each city is visited precisely once, and the start and end points of the route coincide. Looking at this statement, it seems obvious that part of the DESD(OP)^2 optimization problem can be formulated according to the Travelling Salesman Problem:

1. For both types of problems, requirements need to be met (the energy requirements need to be satisfied in the network design and optimization problem, and each city has to be visited in the Travelling Salesman Problem).

2. Both problems involve a network: the pipes of a district energy system or the roads linking cities together.

3. The connection or not of two nodes requires the use of binary variables.

To solve the Travelling Salesman Problem, one algorithm which has shown to solve satisfactorily practical problems is the branch-and-bound algorithm [82, 95]. Due to the above mentioned similarities between the network design and optimization problem, and the Travelling Salesman Problem, the same type of well-proven mathematical tool, namely the branch-and-bound algorithm, shall be used to solve the network part. According to the type of variables included in the network problem to be solved (binary only, or binary and continuous), the branch-and-bound algorithm can be used alone or combined for instance with the Simplex method. In the case of the DESD(OP)^2 optimization problem, both binary and continuous variables are involved in the network part. Therefore, the MILP optimization problem could, in turn, be decomposed into a second decomposition level, in an IP part (design of the network) and an LP part (operation of the energy conversion technologies and network). Practically, this decomposition is automatically performed when using commercial softwares like the Cplex solver [24] used for this thesis, so that no further development is required at this stage. The only issue that is not yet completely solved, is the guarantee of the linearity of all the constraints included in the optimization of the network part, and which needs to be satisfied when using the branch-and-bound method together with the Simplex method. Linearity can indeed only be ensured at the expense of some reasonably posed simplifications, since thermodynamic phenomena, such as heat or pressure losses for instance, which play a role when optimizing the network layout, are de facto not linear. If some of these issues can be overcome by means of some simplifications, as in [26] and explained in Section 4.5, for others, such as the simultaneous optimization of the supply and return temperatures in the network(s) together with the mass flow rates, the issue remains and an appropriate strategy needs to be developed, as explained further down this chapter. Finally, it is important to mention that in the optimal network layout, buildings belonging to the district may be *excluded* from the network for different reasons, as will be shown in Chapters 5 and 6.

Having selected the branch-and-bound algorithm, which belongs to the category of algorithms solving MILP problems, to solve the network sub-problem, the remaining part of the overall DESD(OP)^2 optimization problem is a non linear part and includes above all the district energy conversion technologies. The individual back-up energy conversion technologies are optimized together with the network. They are indeed implemented when the network can't supply the buildings with the required energy. Mathematically, the individual back-up energy conversion technologies ensure the convergence of the network optimization. Therefore, simplified linear models are used for the back-up technologies. Binary variables appear in both the linear part (network) and the non linear part (district energy conversion technologies).

Having defined an appropriate optimization algorithm for the network part, the next step is to choose the optimization algorithm that will take care of the district energy conversion technologies. Remember that the major reason for not choosing the multi-objective evolutionary optimizer MOO for the entire DESD(OP)^2 problem was the too high probability for MOO to choose sets of decision variables resulting in unfeasible solutions, especially for the network. However, having separated the network optimization from the rest of the problem, this issue is not existent anymore, making MOO an interesting tool to solve the remaining part of the DESD(OP)^2 problem, namely the district energy conversion technologies part.

The next question that needs to be addressed now is whether to solve first the network and then the district energy conversion technologies, or vice-versa. To answer this question, the bi-level decomposition is analysed with regard to the DESD(OP)^2 problem.

3.4.3 Bi-level (or hierarchical) decomposition

The bi-level decomposition (also called hierarchical decomposition) includes an *upper level* involving mainly design variables, and a *lower level* involving mainly operation variables [49]. This decomposition strategy thus follows the natural logic implying that the design comes first and the operation second. However, applying this decomposition strategy results in separating the optimization of the network in a design part and an operation part, which again is not meaningful considering the use of the branch-and-bound algorithm for the network part. The idea which is retained however, is to consider, beside the mathematical structure of the problem mentioned above, also a *logical aspect* to define the decomposition strategy. Given the fact that the use of the locally available energy sources is a key factor in the DESD(OP)^2 problem, the choice of the energy conversion technologies can not be fudged, but needs to respect the constraints imposed on the DESD(OP)^2 problem by the location of the district. In other words, it makes less sense to optimize first the network and then see which district energy conversion technologies could be implemented, than the other way round: optimize first the district energy conversion technologies according to the available energy sources, and then the network (even it may mean resorting to individual back-up technologies).

The design of the district energy conversion technologies is to be optimized first, and the network second. Therefore, the optimization of the district energy conversion technologies is called the *master optimization*, and the optimization of the network the *slave optimization*.

3.4.4 Remaining issues... and synthesis of the decomposition

Finally, two last issues need to be addressed: the optimization of the supply and return temperatures of the heating and the cooling distribution networks, and the fact that the branch-and-bound algorithm is a single objective optimization algorithm when the DESD(OP)^2 problem is a multi-objective optimization problem. Regarding the supply and return temperatures, if these parameters were to be optimized by the network optimization algorithm, non linearities would arise that would prevent from using the classic branch-and-bound algorithm. Many constraints indeed imply to multiply the supply or the return temperatures with the mass flow rates. The optimization of these parameters is therefore entrusted to the optimization algorithm that takes care of the design of the district energy conversion technologies, in other words the master optimization. Therefore, as will be explained in Section 4.5, these temperatures become parameters in the slave optimization, preventing the non-linearities from occurring.

Regarding the fact that the branch-and-bound algorithm is a single-objective optimization algorithm, the following procedure has been implemented in order to take into account both objectives also in the slave optimization. As will be explained in details in the next chapter, the objective function of the linear slave optimization is the minimization of the costs. However, a value for a CO_2 weighting factor is given to the slave optimizer by the master optimizer. This CO_2 weighting factor influences the result of the slave optimization towards less CO_2 emitting solutions.

Synthesizing the decomposition strategy of the overall DESD(OP)^2 problem, each part optimizes following decision variables:

Master optimizer:	Type of the district energy conversion technologies
(Evolutionary algorithm)	Size of the district energy conversion technologies
	Parameters related to the district energy conversion technologies
	Supply and return temperatures of the distribution networks CO_2 weighting factor

Slave optimizer: (Branch-and-bound algorithm)	Layout of the pipes
	Flows in the pipes (mass, energy and power)
	Location of the district energy conversion technologies
	Operation strategy of the district energy conversion technologies
	Type of the individual back-up energy conversion technologies
	Location of the individual back-up energy conversion technologies
	Operation strategy of the individual back-up energy conversion technologies

The decision variables optimized in the master optimization belong to the *master set* of decision variables, and the decision variables optimized in the slave optimization to the *slave set* of decision variables. The combination of both sets of decision variables is the *extended set* of decision variables.

Finally, since a short description of evolutionary algorithms has already been given above, no further insights shall be given at this stage. Only the basic concepts underlying the branch-and-bound algorithm used for the slave optimization shall be pointed out hereunder to end this chapter.

3.5 Branch-and-bound algorithm

The branch-and-bound method basically solves a model by breaking up its feasible region into successively smaller subsets (*branching*), calculating bounds on the objective value over each corresponding submodel (*bounding*), and using them to discard some of the submodels from further consideration (*fathoming*). The bounds are obtained by replacing the current submodel by an easier model (*relaxation*), such that the solution of the latter yields a bound for the former [82].

Following the explanation given in the Cplex user's guide [24], which is the solver used in the present thesis, the branch-and-bound algorithm maintains a hierarchy of the linear programming subproblems, referred to as the search tree, and usually visualized as branching downward (Figure 3.3). There is a subproblem at each node of the tree, and each node is explored by solving the associated subproblem. The algorithm starts with just a top (or root) node, whose associated subproblem is the relaxation of the integer program - the LP that results when all integrality restrictions are dropped. If this relaxation happened to have an integer solution, then it would provide an optimal solution to the integer program. Normally, however, the optimum for the relaxation has some fractional valued integer variables. A fractional variable is then chosen for branching, and two new subproblems are generated, each with more restrictive bounds for the branching variable. For example, if the branching variable is binary (0-1), one subproblem will have the variable fixed at zero and the other at one. In the search tree, the two new subproblems are represented by two new nodes connected to the root. Most likely each of these subproblems also has fractional-valued integer variables, in which case the branching process must be repeated; successive branchings produce the tree structure shown in Figure 3.3. If there are more than a few integer variables, the branching process has the potential to create more nodes than any computer can hold. There are two key circumstances, however, in which branching from a particular node can be discontinued:

- The node's subproblem has no fractional-valued integer variables.
- The node's subproblem has no feasible solution, or has an optimum that is worse than a certain cutoff value.

In these cases the node is said to be fathomed. When no active nodes are left, the resolution procedure is finished. Because a single integer program generates many LP subproblems, even small instances can be very compute-intensive and require significant amounts of memory. It can therefore be very helpful to speed up the resolution by the employment of a cutting plane scheme, either just at the top of the tree, or at every node of the tree [68]. A cutting plane is a new constraint, added to the reduced LP problem, that decreases the size of the search space without excluding the optimal solution. Let's assume a problem with x_1 and x_2 being integer variables, and for which an optimal solution has been found to the relaxed problem (the * in Figure 3.4). If none of the integer variables is fractional, then we are done. If some of the integer variables are fractional (which will most likely be the case, as in the figure), then a cutting plane (an additional constraint) is found, that separates the fractional solution from the rest of the search space. With the inclusion of this cutting plane, the former solution is forbidden [31]. In Figure 3.4 the upper right corner of the search space is being cut off, while the lower right part remains in the search space.

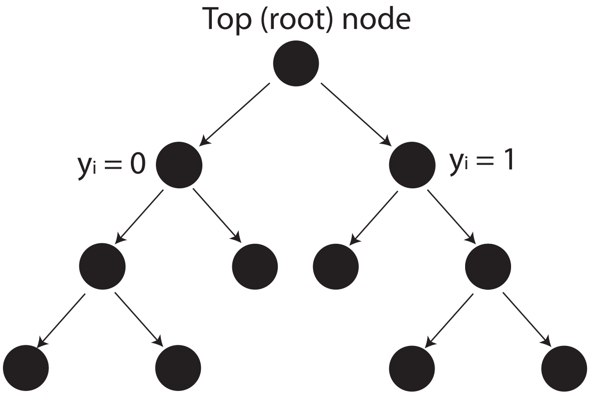

Figure 3.3: Tree representation of the branch-and-bound method (after [25])

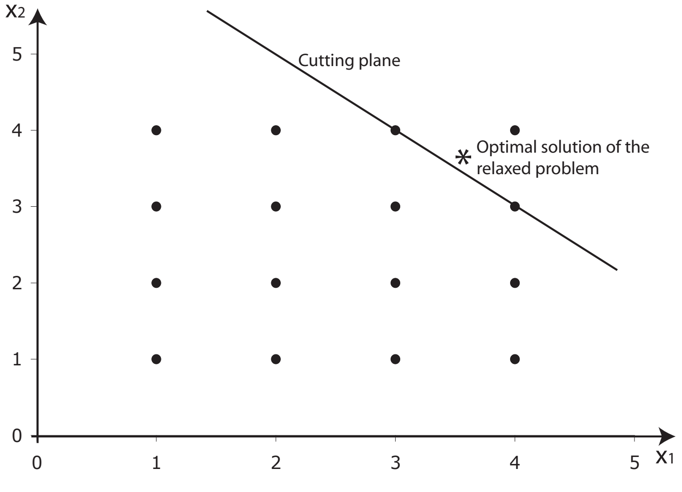

Figure 3.4: Cutting plane [82]

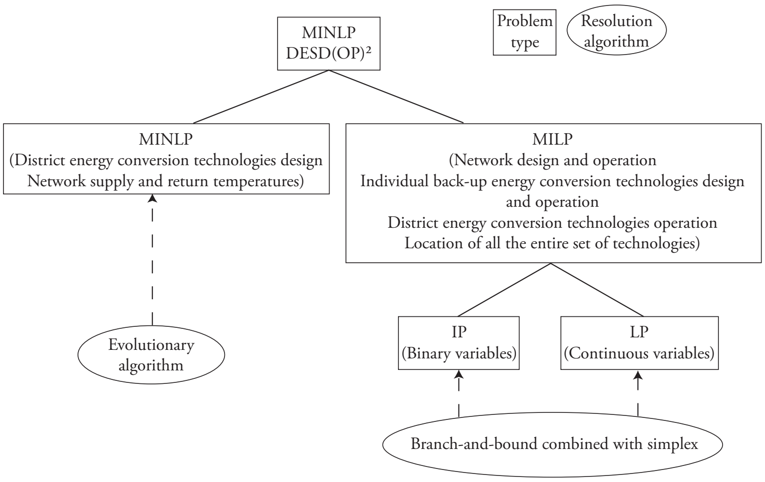

Figure 3.5: Overall decomposition of the DESD(OP)^2 problem

3.6 Conclusion

In this chapter, the decomposition strategy developed to solve the DESD(OP)^2 optimization problem is pictured. The DESD(OP)^2 problem is basically decomposed in two sub-problems, a master optimization sub-problem for the district energy conversion technologies and the network temperatures, and a slave optimization sub-problem for the network design and operation. This decomposition is based on mathematical as well bi-level (hierarchical) aspects of the problem, and includes a heuristic (evolutionary algorithm) as well as a deterministic algorithm (simplex). The developed strategy therefore results in a *hybrid* optimization strategy, combining the advantages of the different optimization algorithms. Figure 3.5 summarises the decomposition strategy, together with the algorithms that are being used to solve each part.

Chapter 4

Mathematical formulation of the optimization phase

4.1 Introduction

Having set up a solution strategy in the previous chapter, this chapter deals with the mathematical formulation of the whole optimization phase. This includes the master and the slave optimizations, the thermo-economic models belonging to the data base of district as well as individual back-up technologies, and a data processing routine. The different elements of the optimization phase are explained in following the order in which they appear Figure 2.1, except for the data processing routine that is explained after the slave optimization although it appears before in the figure. The data processing routine is indeed easier to understand once the formulation of the slave optimization is known.

4.2 The master optimization

4.2.1 Objective function and decision variables

The objective function of the master optimization is the minimization of both the annual CO_2 emissions and the annual cost (multi-objective optimization). The inputs of the master optimization are the list of decision variables with their lower and upper bounds. These decision variables have already been listed in Paragraph 3.4.4 and include: binary variables for the choice of the district energy conversion technologies, and continuous variables for the size of the district energy conversion technologies, various technology related parameters (like the condenser temperature for heat pumps for instance), the temperatures of the networks and the CO_2 weighting factor. Regarding the temperatures, the DESD(OP)^2 method allows to optimize the supply and return temperatures of each network for each period independently. The lower and upper bounds of the *continuous* variables are given in Table 4.1.

Decision variable	Lower bound - upper bound
District energy conversion technologies	Minimum available size (market size) for the technology - Minimum between the maximum requirements and the maximum available market size
Specific technology related, optimization parameters (if any)	
Supply temperature for the heating network for each period	40°C - 120°C
Return temperature for the heating network for each period	30°C - supply temperature of the respective period
Supply temperature for the cooling network for each period	6°C - 20°C
Return temperature for the cooling network for each period	Supply temperature of the respective period - 22°C
CO_2 weighting factor:	0 CHF/kWh - 0.50 CHF/kWh

Table 4.1: Lower and upper bounds of the continuous decision variables optimized by the master optimizer

In the problem formulation, the ranges of all the continuous decision variables have been normed to 0 for the lower bound and 1 for the upper bound, in order to homogenize the ranges of the different decision variables and therefore ensure a better covering up of the search space. Beside the definition of the bounds, the evolutionary algorithm used for the master optimization requires the size of the initial population as well as the number of clusters to be determined. The values for these two latter parameters are set based on knowledge of MOO and experiencing.

4.2.2 Constraints and parameters

The constraints of the master optimization include the models of the district energy conversion technologies (Section 4.3), the equations of the data processing routine (Section 4.5), as well as the slave optimization (Section 4.4).

The parameters include:

- the parameters used in the models of the district energy conversion technologies (exergetic efficiency of heat pumps or isentropic efficiencies of compressors for instance),
- the parameters used in the data processing routine (velocity of the water in the pipes, specific heat of water,....),
- the parameters of the slave optimization (fixed and proportional costs of the

pipes or individual back-up energy conversion technologies for instance).

Except for the thermodynamic parameters, such as the specific heat of water, or else parameters such as the velocity of the water in the pipes, the values of the parameters change from district to district.

4.3 Thermo-economic models of the district energy conversion technologies at the central power plant

The thermo-economic models of the *district* energy conversion technologies[1] are included in the data base of district technologies (see Figure 2.1). They compute the performances and the investment turnkey cost, given the size and any other necessary model parameters (for instance the condenser temperature of a heat pump). The method developed in this thesis is not restricted to the use of models developed on purpose. Basically any model of any author can be implemented, provided that the following outputs are computed:

1. the electrical and thermal efficiencies (ϵ_{el} respectively ϵ_{th}),
2. the temperature level(s) at which heating or cooling is/are delivered,
3. the investment turnkey cost,
4. the minimum part load and its corresponding performances.

If one of the above mentioned information is not available in the model (in particular the investment costs or the part load performances), the missing information has to be completed (for instance with trends provided by manufacturers) and the data base is updated. It is also important to mention at this stage that due to the constraint of linearity imposed by the branch-and-bound algorithm used for the slave optimization, and the fact that the operation strategy of the district energy conversion technologies is computed in the slave optimization, the part load performances of the district energy conversion technologies are approximated so as to vary linearly, or piecewise linearly, between the design size and the minimum part load of the technology.

To develop the method, three types of district energy conversion technologies have mainly been considered, namely heat pumps for heating, as well as gas turbine combined cycle (gas turbine/steam turbine) and gas engines for cogeneration (heating and electricity). Regarding cooling, since the method was developed based on districts situated near lakes (Geneva) or rivers (Martigny), no specific cooling technology was used, other than heat exchangers between the water from the lakes or rivers, and the water circulating in the cooling network, as well as heat pumps that are implemented between the return pipe of the cooling network and the supply pipe

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[1] The district energy conversion technologies are the ones which are implemented at the central power plant and connected to the distribution networks (including the grid).

of the heating network. These heat pumps shall allow to recycle the heat released by the buildings while being cooled down. However, any other type of technology can be added, or "plugged" into the method at any time for any energy service. For instance, if no surface water can be used for cooling purposes, but heat is released from an industrial plant, absorption chillers could be an option. Simplified thermo-economic models for these technologies are explained hereafter and the main assumptions given. The reason for using simplified models, is that the idea when first analysing a district is to explore the range of solutions resulting from the master optimization, before making more detailed analysis. If for instance heat pumps or combined cycles appear to be promising technologies, the results can then be refined with more sophisticated models. In the case of heat pumps, this could be a model including three stage heat pumps equipped with compressors featuring variable inlet guide vanes and diffuser vanes.

4.3.1 Heat pump model

The heat pump model computes the performances of double-stage heat pumps[2] using R134a as refrigerant (R134a being used in over 90% of the large size district heat pumps [75]). The possible design size for such district heat pumps ranges from 1 000 kWth up to 20 000 kWth (data range defined based on manufacturer data [75]).

MODEL ASSUMPTIONS AND PARAMETERS:

1. The intermediate pressure level of the heat pump is defined such that the pressure ratio between the intermediate and the lowest pressure level is the same as the pressure ratio between the highest and the intermediate pressure level (see Figure 4.1 for which the pressure ratio equals 2.52).
2. The exergetic efficiency of district heat pumps, η^{HP}, amounts to 0.6 (average value based on manufacturer data [75]).
3. The maximum design temperature in the condenser amounts to 90°C [75].
4. The pinch in the evaporator amounts to 2°C.
5. The isentropic efficiency of the compressor amounts to 0.87.
6. The proportion of sub-cooling in the higher pressure evaporator is half of the difference between the saturated liquid enthalpy at the higher pressure level and the saturated liquid enthalpy at the intermediate pressure level (see Figure 4.1).
7. Whenever the temperature decrease that can be achieved on the low temperature heat source exceeds 5°C, two heat pumps are implemented in series. In this case, each heat pump is responsible for half of the temperature decrease of the heat source (Figure 4.2 shows an example for which the low temperature heat source at the evaporator is water from a wastewater treatment facility, in which a temperature difference of 10°C can be gained from the wastewater).

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[2] This simplification is reasonable since the models defined here are simplified models. Two of the largest heat pumps installed to-day feature indeed a nominal capacity of 45 MWth with three stage centrifugal compressors, and are located in Göteborg/Sweden.

8. The part load operation is defined by the duration of operation of the heat pump[3].
9. The lifetime for heat pumps has been set to 25 years and the interest rate to 0.06.

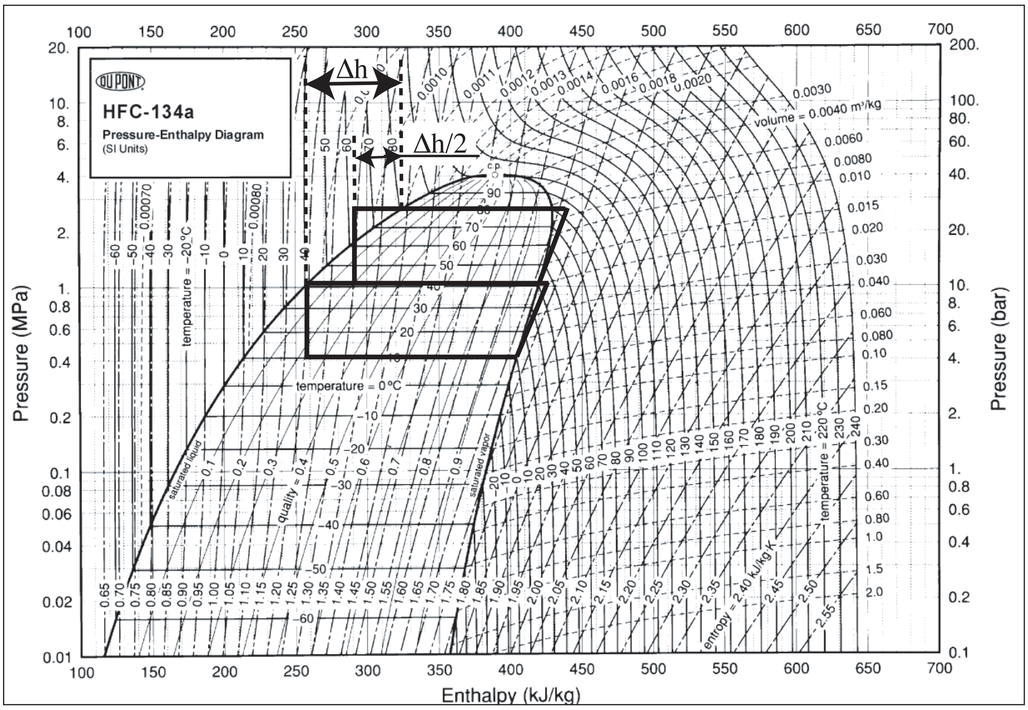

Figure 4.1: Cycle of a double-stage heat pump using R134a, and featuring an evaporator temperature of 10°C and a condenser temperature of 80°C

Model:
Coefficient of performance of the heat pump, with η^{HP} the exergetic efficiency:

$$COP = \eta^{HP} \cdot \frac{T^{\text{cond}}}{T^{\text{cond}} - T^{\text{evap}}} \qquad [\text{-}] \tag{4.1}$$

To compute the investment turnkey cost, correlations based on manufacturer data has been used [75] (with S^{HP} the design size of the heat pump, c^{HP} the specific investment turnkey cost and C^{HP} the investment turnkey cost):

$$c^{\text{HP}} = -493.53 \cdot \ln S^{\text{HP}} + 5484 \qquad [\text{CHF/kWth}] \tag{4.2}$$

$$C^{\text{HP}} = c^{\text{HP}} \cdot S^{\text{HP}} \qquad [\text{CHF}] \tag{4.3}$$

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[3] In a more detailed model, a full compressor map with variable inlet guide vanes or variable inlet and diffuser vanes would be considered, allowing almost the full coverage of the demand in continuous operation.

If the size of the heat pump exceeds the maximum equipment size of 20 000 KWth, the specific cost for a heat pump of 20 000 kWth is considered to compute the investment cost and several heat pumps are implemented. Besides, if the temperature decrease of the low temperature heat source exceeds 5°C and two heat pumps are implemented in series instead of only one (Point 7 above), the specific turnkey cost is computed considering the total size of both heat pumps together.

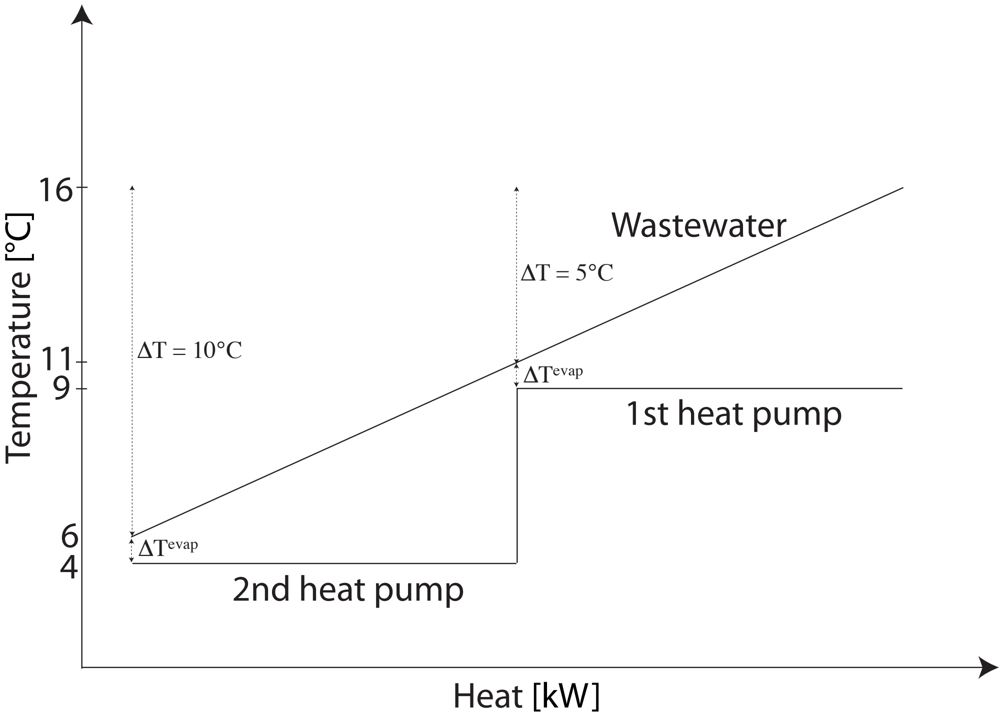

Figure 4.2: Two heat pumps in series connected to a wastewater treatment facility

4.3.2 Combined cycle model

The combined cycle model computes the performances of a combined cycle with municipal heat recovery, including a gas turbine and a double pressure steam turbine as depicted in Figure 4.3 . The possible design size ranges from 20 000 kWel up to 50 000 kWel (these bounds are defined according to the correlations used in the model and published in [73, 58]).

MODEL ASSUMPTIONS AND PARAMETERS:

1. The pressure ratio of the air compressor amounts to $\pi^C = 14.2$ [73].
2. The isentropic efficiency of the gas turbine amounts to $\epsilon_{\text{is}}^{GT} = 0.9$, the isentropic efficiency of the steam turbine to $\epsilon_{\text{is}}^{ST} = 0.9$, and the isentropic efficiency of the compressor to $\epsilon_{\text{is}}^{Comp} = 0.87$ [41].
3. The pressure of the exhaust gas after the gas turbine is the atmospheric pressure [73] (assimilated to a pressure of 1 bar).

4. The air factor for the combustion of the natural gas amounts to 1.8 [73].
5. The minimum temperature difference in the heat recovery steam generator between the exhaust gas and the steam, ΔT_{Exhst}, amounts to 4°C.
6. If different supply temperatures ($T_{\mathrm{hs},t}$) are chosen for the district heating network in winter and in summer, the winter supply temperature is selected to define the condenser temperature (after the steam turbine).
7. The minimum temperature difference in the condenser between the steam and the district heating network equals 2°C.
8. The exhaust gas are assumed to behave like a perfect gas.
9. The minimum part-load amounts to 70%, based of the gas turbine.
10. In the heat recovery steam generator, the lower pressure evaporator is at a pressure of 6 bar and the higher pressure evaporator at a pressure of 48.2 bar [73].
11. The lifetime for combined cycles has been set to 25 years and the interest rate to 0.06.

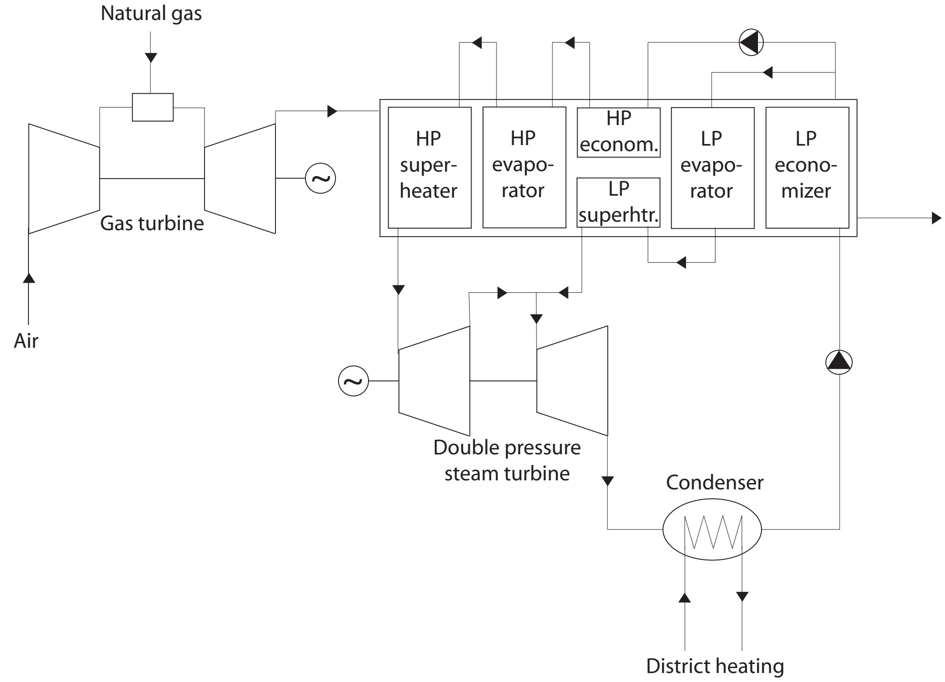

Figure 4.3: Combined cycle with municipal heat recovery including a gas turbine and a double pressure steam turbine

Model:

Gas turbine electrical efficiency at design size, with S^{GT} the design size in kWel of the gas turbine:

$$\epsilon_{\mathrm{el}}^{GT^0} = 0.0196 \cdot \ln S^{\mathrm{GT}} + 0.1317 \qquad (4.4)$$

Correlation 4.4 is based on data from Alstom (GT8C2, GT13E2 and GT26), as well as Pelster [73].

The mass flow rate of air, fuel and exhaust gas are computed knowing the electrical efficiency $\epsilon_{\text{el}}^{GT^0}$ (and therefore the mass flow rate of natural gas), as well as the chemical reaction formula given in Equation 4.5, and considering an air factor of 1.8.

$$\begin{aligned}&(87.4CH_4 + 4.7C_2H_6 + 1.2C_3H_8 + 0.5C_4H_{10} + 4.9N_2 + 1.3CO_2) + \\ &(1.997(O_2 + 3.773N_2)) \rightarrow 103.3CO_2 + 195.4H_2O + 8.673N_2\end{aligned} \tag{4.5}$$

The temperature of the air at the outlet of the compressor is computed using the following Equation [11], in which π^C is the pressure ratio in the compressor, τ^C the temperature ratio, and γ the calorific ratio:

$$\epsilon_{\text{is}}^{Comp} = \frac{(\pi^C)^{\frac{\gamma-1}{\gamma}} - 1}{\tau^C - 1} \tag{4.6}$$

The combustion temperature of the exhaust gas at nominal load, T_{Gas}^{comb}, can be approximated using Equation 4.7, in which $\hat{h}_{fuel}$ and $\hat{h}_{air}$ represent the surenthalpy of the fuel, respectively of the air:

$$\dot{M}_{Exhst}^{\text{GT}^0} \cdot cp_{Exhst}^{\text{GT}} \cdot T_{Gas}^{\text{comb}} = \dot{M}_{fuel}(\Delta h_{fuel}^{\text{lhv}} + \hat{h}_{fuel}) + \dot{M}_{air} \cdot \hat{h}_{air} \tag{4.7}$$

In Equation 4.7, the surenthalpy of the air, $\hat{h}_{air}$, is computed knowing its temperature given by Equation 4.6.

Knowing the combustion temperature, the temperature of the exhaust gas after the gas turbine can be computed by means of Equation 4.8, in which π^{GT} is the pressure ratio in the turbine, τ^{GT} the temperature ratio and γ the calorific ration (like above):

$$\epsilon_{\text{is}}^{GT} = \frac{1 - \tau^{GT}}{1 - (\pi^{GT})^{\frac{\gamma-1}{\gamma}}} \tag{4.8}$$

For the steam turbine model, a double pressure turbine with reheat has been chosen. Figure 4.4 shows schematically the hot and the cold composite curves of the exhaust gas from the gas turbine and the water/steam used in the steam turbine. The thick lines between points 1-2, 3-4 and 5-6 indicate that the entire mass flow rate of water/steam (from the high pressure *and* the low pressure steam turbines) are heated up, whereas the thin lines between points 2-3 and 4-5 show that only a part of the mass flow rate of water/steam gets heat from the hot exhaust gas, namely the part being expanded in the lower pressure steam turbine (2-3), or the part being expanded in the higher pressure steam turbine (4-5).

The mass flow rates of steam are given by Equations 4.9 (high pressure) and 4.10 (low pressure). The numbers of the indices x for $T_{H_2O}^x$ and ΔT_{Exhst}^x refer to the numbers in Figure 4.4:

$$\begin{aligned}&\dot{M}^{\mathrm{GT}^0}_{Exhst} \cdot cp^{\mathrm{GT}}_{Exhst} \cdot ((T^6_{H_2O} + \Delta T^6_{Exhst}) - (T^4_{H_2O} + \Delta T^4_{Exhst})) = (\dot{M}^{\mathrm{hp}}_{H_2O} \cdot \Delta h^{\mathrm{evap,hp}}_{H_2O})\\ &+(\dot{M}^{\mathrm{hp}}_{H_2O} \cdot (h^{\mathrm{hp},6}_{H_2O} - h^{\mathrm{hp},5}_{H_2O})) + (\dot{M}^{\mathrm{lp}}_{H_2O} \cdot (h^{\mathrm{lp},6}_{H_2O} - h^{\mathrm{lp},5}_{H_2O}))\end{aligned} \tag{4.9}$$

$$\begin{aligned}&\dot{M}^{\mathrm{GT}^0}_{Exhst} \cdot cp^{\mathrm{GT}}_{Exhst} \cdot ((T^4_{H_2O} + \Delta T^4_{Exhst}) - (T^2_{H_2O} + \Delta T^2_{Exhst})) = (\dot{M}^{\mathrm{lp}}_{H_2O} \cdot \Delta h^{\mathrm{evap,lp}}_{H_2O})\\ &+(\dot{M}^{\mathrm{lp}}_{H_2O} \cdot (h^{\mathrm{lp},4}_{H_2O} - h^{\mathrm{lp},3}_{H_2O})) + (\dot{M}^{\mathrm{hp}}_{H_2O} \cdot (h^{\mathrm{hp},4}_{H_2O} - h^{\mathrm{hp},3}_{H_2O}))\end{aligned} \tag{4.10}$$

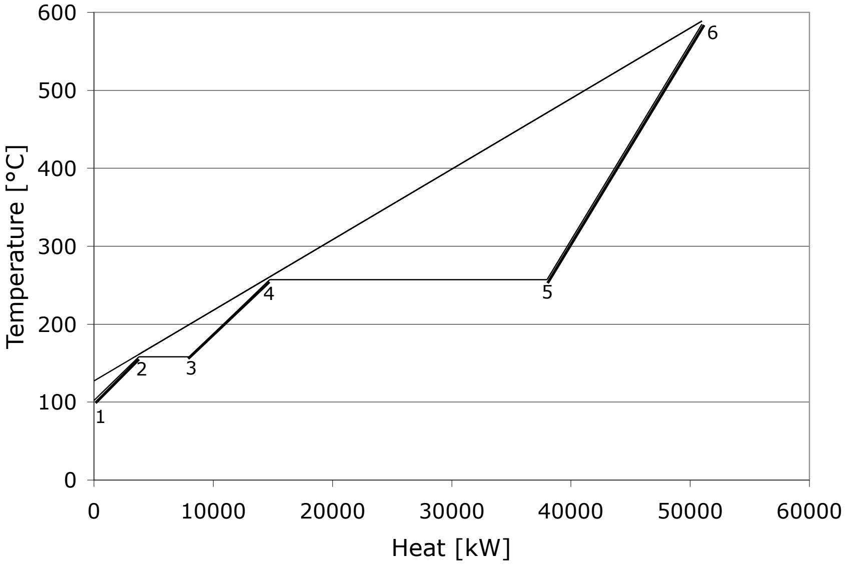

Figure 4.4: Hot and cold composite curves of the exhaust gas from the gas turbine and the water/steam of the steam turbine

Heat provided by the combined cycle to the district heating network ($\Delta h^{\mathrm{evap,cp}}_{H_2O}$ is the latent heat at the pressure prevailing in the condenser):

$$\dot{Q}^{\mathrm{CC}}_{\mathrm{hs}} = (\dot{M}^{\mathrm{lp}}_{H_2O} + \dot{M}^{\mathrm{hp}}_{H_2O}) \cdot \Delta h^{\mathrm{evap,cp}}_{H_2O} \tag{4.11}$$

To compute the part load performances of the combined cycle, the part load performances of the gas turbine are computed first, using the following correlations for the electrical efficiency of the gas turbine (Equation 4.12), the mass flow rate of the exhaust gas (Equation 4.13), and the temperature of the exhaust gas after the gas turbine (Equations 4.14) [58]:

$$\epsilon^{GT}_{\mathrm{el}} = (\epsilon_0 + \epsilon_1 \cdot \kappa_{GT} + \epsilon_2 \cdot {\kappa_{GT}}^2) \cdot \epsilon^{GT^0}_{\mathrm{el}} \tag{4.12}$$

with $\epsilon_0 = 0.4089$, $\epsilon_1 = 0.9624$ and $\epsilon_2 = -0.3726$, and κ_{GT} the part load factor.

$$\dot{M}^{\mathrm{GT}}_{Exhst} = (\mu_0 + \mu_1 \cdot \kappa_{GT}) \cdot \dot{M}^{\mathrm{GT}^0}_{Exhst} \tag{4.13}$$

with $\mu_0 = 0.9934$ and $\mu_1 = 0.0066$.

$$T^{\mathrm{GT}}_{Exhst} = (\tau_0 + \tau_1 \cdot \kappa_{GT}) \cdot T^{\mathrm{GT}^0}_{Exhst} \tag{4.14}$$

with $\tau_0 = 0.7379$ and $\tau_1 = 0.2621$.

To compute the performances of the steam turbine when the combined cycle is operated at part load, the same steam turbine model is used as for the full load operation, however with the values for the exhaust gas temperature and mass flow rate of the gas turbine computed with Equations 4.12 to 4.14.

To compute the investment turnkey cost of the combined cycle, the cost of the gas turbine, the steam turbine, and the civil engineering and auxiliary equipment cost are summed up according to Equation 4.15 [73]. The cost for the gas turbine and the steam turbine are related to the design size of each piece of equipment, whereas the cost for the civil engineering and auxiliary equipment are related to the size of the combined cycle (in kWel). The following correlation has been used for each of the three elements:

$$C^{\mathrm{CCGT}} = C^{\mathrm{GT}} + C^{\mathrm{ST}} + C^{\mathrm{CE}} \quad [\mathrm{CHF}] \tag{4.15}$$

$$\frac{C}{C^{\mathrm{ref}}} = \left(\frac{S}{S^{\mathrm{ref}}}\right)^{0.6} \tag{4.16}$$

The reference parameters that have been used are given in Table 4.2[4] [73]:

	Size	Cost
Gas turbine	145 kWel	33.7 mio-CHF
Steam turbine	82 kWel	43.4 mio-CHF
Civil eng. and auxiliaries	227 kWel	138 mio-CHF

Table 4.2: Reference sizes and costs used to compute the investment cost of the combined cycle [73]

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[4] The cost have been actualised with the Marshall-Swift factor and converted from USD to CHF [101] in the model. The original costs in USD are: gas turbine: 27.2 mio-USD, steam cycle: 35 mio-USD, civil engineering and auxiliaries: 111 mio-USD

4.3.3 Gas engine

The gas engine model computes the performances of lean burn gas engines used for cogeneration. The possible design size ranges from 1 000 kWel up to 5 000 kWel [16].

Model assumptions and parameters:

1. The minimum part load of the gas engine is set to 60% of the design load ([79, 45]).
2. The sum of the electrical and thermal efficiencies equal 90% regardless of the part load factor.
3. The air factor for the combustion of the natural gas amounts to 1.5 [2].
4. The electrical efficiency at the minimum part load of 60% amounts to 93% of the electrical efficiency at full load ([19, 79]).
5. The temperature of the exhaust gas amounts to an average value of 550°C [63] and may be cooled down to 40°C.
6. The temperatures of the cooling circuit of the engine amount to 90°C (inlet temperature) and 100°C (outlet temperature).
7. The total heat recovered for heating purposes includes 38% coming from the exhaust gas and 62% from the cooling circuit at design load [32], the same proportions are applied at part load operation.
8. The lifetime for gas engine has been set to 25 years and the interest rate to 0.18 (computed on the basis of a maintenance cost of 0.03 CHF/kWhel [26]).

Model:
Gas engine efficiency at design size, with S^{GE} the design size of the gas engine in kWel (correlation based on [66]):

$$\epsilon_{el}^{\mathrm{GE}^0} = 0.016 \cdot \ln S^{\mathrm{GE}} + 0.30932 \tag{4.17}$$

To compute the investment turnkey cost of the gas engine, a correlation based on [3, 2] has been used:

$$c^{\mathrm{GE}} = 16225 \cdot (S^{\mathrm{GE}})^{-0.3754} \qquad [\mathrm{CHF/kWel}] \tag{4.18}$$

$$C^{\mathrm{GE}} = c^{\mathrm{GE}} \cdot S^{\mathrm{GE}} \qquad [\mathrm{CHF}] \tag{4.19}$$

4.4 The slave optimization

4.4.1 Objective function and decision variables

The objective function minimises the annual operating costs and the annual investment costs, minus the income I^{el} of the excess electricity generated by the district energy conversion technologies. The annual operating costs include the costs for the natural gas, the grid, the oil and the penalty for the CO_2 emissions[5].). The annual investment costs include the costs for the pipes, circulation pumps, heat-exchangers and individual back-up energy conversion technologies (air/water heat pumps, water/water heat pumps, boilers and chillers).

$$\begin{aligned}\min \big(&C^{\text{gas}} + C^{\text{grid}} + C^{\text{oil}} + C^{\text{CO}_2} - I^{\text{el}} + \\ &C^{\text{pipes}} + C^{\text{pump}} + C^{\text{hex}} + C^{\text{aw}} + C^{\text{ww}} + C^{\text{boiler}} + C^{\text{chiller}}\big) \quad [\text{CHF/year}] \qquad (4.20)\end{aligned}$$

Like many MILP solvers, the solver used in the present thesis, Cplex, uses various heuristics to estimate how far from the optimum the solution of a subproblem of the search tree really is (see Section 3.4). The optimal value of an integer program is indeed bounded on one side by the best integer value found so far, and on the other side, by a value deduced from all the other node subproblems solved so far [25]. When running thousands of iterations with the master optimizer, the time gained by accepting a "good" value from the slave optimizer, instead of the best value, is considerable. Depending on the parameters passed over by the master optimizer, a "good" solution, namely a solution that lies within a certain percentage of the optimal solution in the slave optimization, can be computed in a few seconds or minutes, whereas the optimal solution will take at least half an hour[6]. Therefore, in the present thesis, unless other specified, the precision of the optimization for the slave optimization has been set to 5%.

The decision variables optimized in the slave optimization have already been listed in Paragraph 3.4.4. They include the layout of the pipes, the location of the technologies (district and back-up) and the periodic operation strategy and performances of the entire set of technologies (district and back-up), in order to meet the energy requirements of the buildings. Regarding the decision variables related to the individual back-up energy conversion technologies, following important comment has to be done at this stage: Because the design sizes of the individual back-up energy conversion technologies are optimized in the slave optimization, which is a Mixed Integer *Linear* programming optimization problem, simplified *linear* relations are used to compute the performances of these technologies (boilers, heat pumps and chillers), as can be seen for instance in Equations 4.42 or 4.45. This constraint clearly distinguishes these technologies from the district energy conversion technologies, for which any model can be used.

4.4.2 Inputs and parameters of the slave optimization

The inputs and parameters used in the slave optimization include the results (outputs) of the structuring phase, the outputs resulting from the thermo-economic models and data processing routine pursuant the values given by the master optimization to the master set of decision variables, and thermodynamic parameters.

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[5] Remember that in order to account for the second objective, namely the annual CO_2 emissions, a weighting factor has been introduced in the slave optimization as explained in Section 3.4.4.

[6] These time estimations refer to computers featuring Intel Pentium4 processors, 2'800 MHz, with 2 GB memory [76]

1. Outputs from the structuring phase (seen from the slave optimizer, Items 1a to 1d are rather inputs and Items 1e and 1f parameters):

    (a) Energy consumption profiles: this includes the average hourly heat rate, hot water rate, cooling rate and electricity rate, together with the temperature levels (for the thermal requirements), as well as the duration of each period of the profile, in hours per year. The year is indeed divided in a certain number of periods which can all have different durations.

    (b) Eligible locations for the district energy conversion technologies: the parameters referring to the possible hosting by a node of district energy conversion technologies is set to 1 if the node is eligible and 0 otherwise.

    (c) Connections: All the connections between two nodes which are eligible (see Section 2.2) have to be listed with their respective length. If an existing pipe is already connecting two buildings, the existence of this pipe is also mentioned, thus avoiding for the slave optimization to compute the investment costs of this very connection if it appears to be selected in the optimal solution.

    (d) Already existing heat-exchangers between the network(s) and the consumer(s): if a network is already existing, meaning that heat-exchangers are already installed at some nodes and don't need to be invested for anymore, the corresponding parameter for these nodes is set to 1 (0 otherwise).

    (e) Individual back-up energy conversion technologies: for heating, hot water and cooling, one or more back-up device(s) is/are given with their respective investment cost parameters and energetic or exergetic efficiencies (the coefficients of performance are computed directly in the slave optimization). The efficiencies and coefficients of performance are assumed constant regardless of the part load factor. For electricity, the grid is used as back-up[7].

    (f) Costing and CO_2 emissions: All the parameters that are requested to compute the investment costs of the pipes, the pumps and the individual back-up devices are listed. These include, the fixed costs, the proportional costs, the Marshall-Swift factors, the interest rates and the lifetimes in years. For the operating costs, the price for natural gas, electricity from the grid, and oil, are given. Periodic (time dependent) variations can be taken into account for these latter costs. Besides, the specific CO_2 emissions generated by the use of one kWh of natural gas, electricity from the grid or oil are also given.

2. Outputs from the thermo-economic models and data processing routine pursuant the values given by the master optimization to the master set of decision variables (seen from the slave optimizer Items 2a to 2e are rather inputs and Items 2f to 2h parameters):

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[7] The grid is used both to buy and sell electricity.

   (a) District energy conversion technologies: All the data regarding the district energy conversion technologies selected by the master optimization, such as design load, part load performances, thermal and electrical efficiencies, distributed energy type required (natural gas or electricity) are listed,
   (b) Supply and return temperatures of the heating and cooling networks,
   (c) Possibility to connect a building to the network, considering the temperature levels of the thermal requirements of the buildings on one side, and of the network on the other side,
   (d) Bounds related to the process integration (temperature intervals with their upper and lower temperature levels),
   (e) Costing: costs of the heat-exchanger (see Paragraph 4.5.1),
   (f) Average specific heat losses,
   (g) Average specific pressure losses,
   (h) Upper and lower bounds of the continuous variables to speed up the convergence of the binary variables.

3. Thermodynamic parameters: specific heat of water, density of water, minimum temperature difference at the heat exchangers, average specific heat loss, average specific pressure drop and velocity of the water in the pipes.

4.4.3 Constraints of the slave optimization

The following types of constraints have been defined in the slave optimization:

1. Energy balances
   - First Law[8] thermal energy balances
   - Energy cascades
   - Electrical energy balances
2. Mass balances
3. Connections of nodes and implementation/location of the technologies (district and back-up technologies)
4. Performance functions (costing and CO_2 emission)
5. Empirical (engineer knowledge based) constraints

The energy and mass balances are thermodynamic constraints (the energy cascades refer to the aspects of process integration). The performance functions link the thermodynamic constraints with the objective function. They compute the costs and CO_2 emissions generated when satisfying the energy requirements. Finally, the empirical constraints include the experience of the programmer/engineer in the optimization, speeding up the convergence. The following indexes are used in the constraints given in the remaining part of this section:

1. period: t

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[8] *First Law* of the thermodynamic.

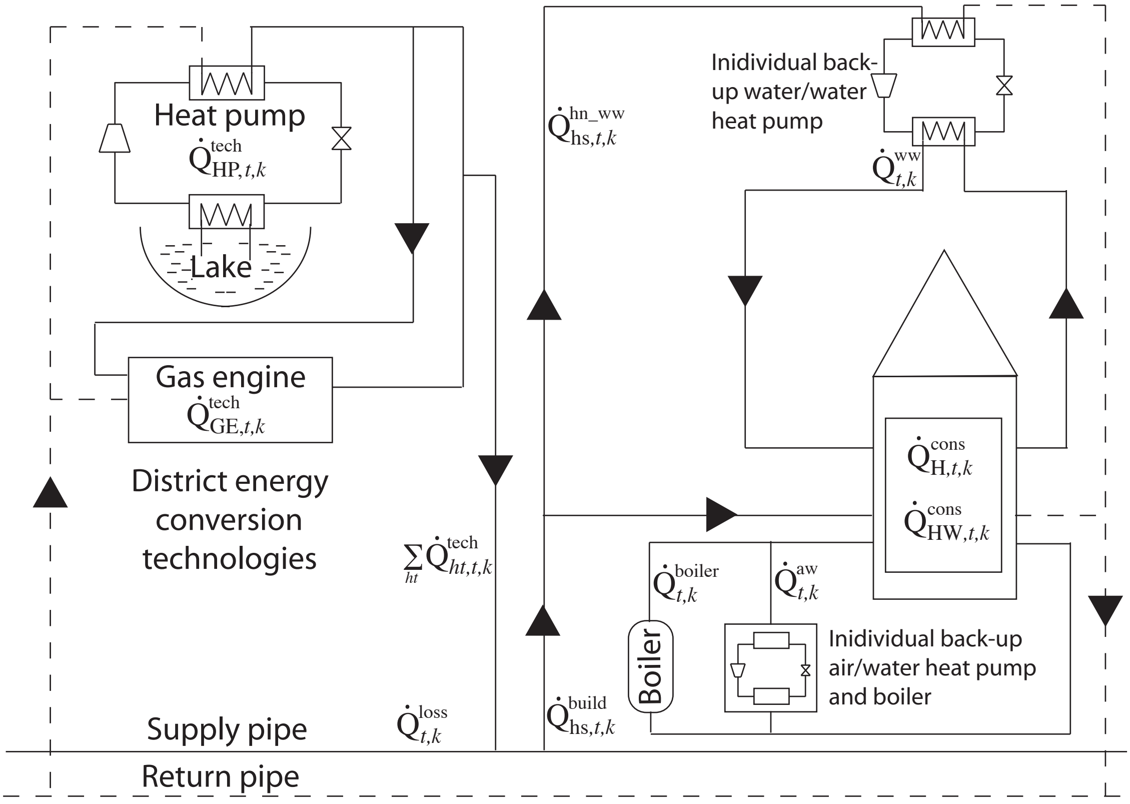

Figure 4.5: Superstructure of a node (the plain lines refer to the supply part of the distribution network and the dotted lines to the return part)

2. node: k
3. connection: i, j
4. temperature interval: d

First principal thermal energy balances

Preliminary comment: following the theory of exergy, for which both the heating and the cooling provided to a building as energy services are *delivered exergies* and both have a positive sign, the heating *and* the cooling energy services will have a positive sign in the following energy balances, when they are provided by the district energy conversion technologies to the distribution networks, and by the distribution networks to the buildings. In other words, the heat provided for heating purposes and the cooling provided for cooling purposes have the same sign, although in the first case energy is given *to* the building whereas in the second case energy is taken *from* the building.

To visualise the different terms entering the energy balances, Figure 4.5 shows an example of the superstructure, for heating and hot water, that can be found at a node where district energy conversion technologies may be located. In the case represented, the district technologies are a heat pump connected to the lake and a gas engine. (To avoid overloading the figure, the cooling technologies (district and/or back-up), the cooling network, as well as the grid, have not been represented.)

Energy balances at the consumer's place

Energy balances are defined for heating and hot water requirements (indices H and HW in Equation 4.21), as well as for cooling requirements (index C in Equation 4.22). These energy balances link the energy required by a node, with the energy provided by the network $\dot{Q}^{\text{build}}_{\text{hs},t,k}$, respectively $\dot{Q}^{\text{cons}}_{C,t,k}$, or the energy provided by the individual back-up technologies ($\dot{Q}^{\text{ww}}_{t,k}$, $\dot{Q}^{\text{aw}}_{t,k}$, or $\dot{Q}^{\text{boiler}}_{t,k}$ for heating, and $\dot{Q}^{\text{chiller}}_{t,k}$ for cooling). $\dot{Q}^{\text{loss}}_{t,k}$ represents all the losses that occur in the heating distribution network, and that are compensated for by the district energy conversion technologies located at node k, if any (heat "losses" have been neglected for the cooling network).

Heating and hot water:

$$\dot{Q}^{\text{cons}}_{H,t,k} + \dot{Q}^{\text{cons}}_{HW,t,k} + \dot{Q}^{\text{loss}}_{t,k} = \dot{Q}^{\text{build}}_{\text{hs},t,k} + \dot{Q}^{\text{aw}}_{t,k} + \dot{Q}^{\text{ww}}_{t,k} + \dot{Q}^{\text{boiler}}_{t,k} \qquad \forall t,k \tag{4.21}$$

Cooling:

$$\dot{Q}^{\text{cons}}_{C,t,k} = \dot{Q}^{\text{build}}_{\text{cs},t,k} + \dot{Q}^{\text{chiller}}_{t,k} \qquad \forall t,k \tag{4.22}$$

ENERGY BALANCES BETWEEN THE CONSUMERS AND THE NETWORK

For the buildings connected to the network, the following balances link the energy supplied by the networks (heating and cooling) to the buildings, with the mass flow rate of water flowing from the networks to the buildings. In the following equations, $T_{\text{hs},t}$ and $T_{\text{hr},t}$ are the supply, respectively return, temperatures of the heating network, and $T_{\text{cs},t}$ and $T_{\text{cr},t}$ the supply and return temperatures of the cooling network.

Heat supplied by the network to the building:

$$\dot{Q}^{\text{build}}_{\text{hs},t,k} = \dot{M}^{\text{build}}_{\text{hn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \forall t,k \tag{4.23}$$

Heat supplied by the heating network to the water/water heat pump in case individual back-up water/water heat pumps locally increase the temperature level of the network:

$$\dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} = \dot{M}^{\text{hn\_ww}}_{\text{hn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \forall t,k \tag{4.24}$$

with:

$$\dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} = \left(1 - \frac{1}{COP^{\text{ww}}_{t,k}}\right) \cdot \dot{Q}^{\text{ww}}_{t,k} \qquad \forall t,k \tag{4.25}$$

and:

$$COP^{\text{ww}}_{t,k} = \eta^{hp} \cdot \frac{T_{Hs,t,k} + \Delta T}{T_{Hs,t,k} - T_{\text{hr},t}} \forall t,k \tag{4.26}$$

where η^{hp} is the exergetic efficiency of the heat pump, $T_{Hs,t,k}$ is the supply temperature of the hydronic circuit in the building, and $T_{\text{hr},t}$ the return temperature of the heating network.

Cooling supplied by the network to the building:

$$\dot{Q}^{\text{build}}_{\text{cs},t,k} = \dot{M}^{\text{build}}_{\text{cn},t,k} \cdot cp^{\text{liq}}_{H_2O} \cdot (T_{\text{cr},t} - T_{\text{cs},t}) \forall t, k \tag{4.27}$$

Energy balances at the plant node[9]
Heat provided by the district technology ht at node k to the heating network:

$$\dot{Q}^{\text{tech}}_{ht,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{hn},t,k} \cdot \Delta T_{ht} \qquad \forall t, ht, k \tag{4.28}$$

Heat provided by the sum of all the technologies at node k to the heating network:

$$\sum_{ht} \dot{Q}^{\text{tech}}_{ht,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{hn},t,k} \cdot (T_{\text{hs},t} - T_{\text{hr},t}) \qquad \forall t, k \tag{4.29}$$

Cooling provided by the technology ct at node k to the cooling network:

$$\dot{Q}^{\text{tech}}_{ct,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{cn},t,k} \cdot \Delta T_{ct} \qquad \forall t, ct, k \tag{4.30}$$

Cooling provided by the sum of all the technologies at node k to the cooling network:

$$\sum_{ct} \dot{Q}^{\text{tech}}_{ct,t,k} = cp^{\text{liq}}_{H_2O} \cdot \dot{M}^{\text{tech}}_{\text{cn},t,k} \cdot (T_{\text{cr},t} - T_{\text{cs},t}) \qquad \forall t, k \tag{4.31}$$

In Equations 4.28 and 4.30, the temperature increase ΔT_{ht}, respectively temperature decrease ΔT_{ct}, generated by the district energy conversion technology is a result of the resolution of the heat-cascade. Let us assume, for instance, that the slave optimizer gets following district energy conversion technologies as input: a heat pump HP with a condenser temperature of 80°C, together with a gas engine GE. Besides, the supply temperature of the heating network amounts to 90°C and the return temperature to 60°C. The heat pump HP can provide the energy to increase the temperature of the heating network from the returning 60°C up to 80°C ($\dot{Q}^{\text{tech}}_{\text{HP,Th3}}$ in Figure 4.6), and the gas engine GE the remaining energy to lift the temperature from 80°C up to the required 90°C ($\dot{Q}^{\text{tech}}_{\text{GE,Th2}}$ and $\dot{Q}^{\text{tech}}_{\text{GE,Th1}}$ in the same figure).

Energy balances around a node
The following energy balances are defined at each node for the heating and cooling networks between to the energy leaving the node on one side (left hand side of the = sign), and the energy arriving at the node, consumed by the node, and provided by the node if a district energy conversion technology is located at that node, on the other side (right hand side of the = sign).

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[9] The term *plant* is used to designate a node where district energy conversion technologies are implemented. A given node can be simultaneously a plant node and a consumer node as shown on Figure 4.5.

Heating supply network hs:

$$\sum_{(k,j)} \dot{Q}_{\mathrm{hs},t,k,j} = \sum_{(i,k)} \dot{Q}_{\mathrm{hs},t,i,k} - (\dot{Q}^{\mathrm{build}}_{\mathrm{hs},t,k} + \dot{Q}^{\mathrm{hn\_ww}}_{\mathrm{hs},t,k}) + \dot{Q}^{\mathrm{tech}}_{ht,t,k} \qquad \forall t, k \tag{4.32}$$

Cooling supply network cs:

$$\sum_{(k,j)} \dot{Q}_{\mathrm{cs},t,k,j} = \sum_{(i,k)} \dot{Q}_{\mathrm{cs},t,i,k} - \dot{Q}^{\mathrm{build}}_{\mathrm{cs},t,k} + \dot{Q}^{\mathrm{tech}}_{ct,t,k} \qquad \forall t, k \tag{4.33}$$

HEAT LOSSES
The heat losses for each period in the heating network[10], are computed by multiplying the specific heat losses (Equation 4.94) with the total length of the network:

$$\dot{Q}^{\mathrm{loss}}_{t} = \sum_{(i,j)} Dist_{i,j} \cdot X_{\mathrm{hs},i,j} \cdot \dot{q}^{\mathrm{loss}}_{t} \qquad \forall t \tag{4.34}$$

In order to be able to integrate these heat losses to the energy balance given in Equation 4.21, they are attributed as an additional energy requirement to the node hosting the district energy conversion technologies (therefore $\sum_{k} \dot{Q}^{\mathrm{loss}}_{t,k} = \dot{Q}^{\mathrm{loss}}_{t}$).

Energy cascade constraints

The energy cascade constraints ensure the energetic integration between the district energy conversion technologies and the distribution networks on one side, and between the distribution networks and the requirements at each (connected) node on the other side. For the energy cascades, the same sign convention has been applied as for the energy balances, namely that both, heating (for heating purposes and hot water) and cooling, have a positive sign when they are provided as energy services. Figure 4.6 shows, by means of an example for heating and hot water requirements, the composite curves involved in the energy cascades, when the following conditions are assumed:

- Average hourly rate of heating requirements: 380 kW between 35°C and 45°C.
- Average hourly rate of hot water requirements: 120 kW between 10°C and 60°C.
- Temperatures of the heating network: 90°C for the supply and 60°C for the return.
- District technologies: a heat pump and a gas engine (see above).

Symmetrically, the same type of diagram can be plotted for the cooling requirements as shown on Figure 4.7: the requirements of the building amount to 200 kW between 18°C and 21°C, the supply and return temperatures of the network amount

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[10] The heat losses in the cooling network have been neglected.

to 19°C respectively 14°C, and the water from the lake used for the cooling increases from 8°C to 17°C.

Energy cascade between the district heating technologies and the heating network for each temperature interval:

$$\sum_{ht}\sum_{k}\dot{Q}^{\mathrm{tech}}_{ht,t,k,d}+\dot{Q}^{\mathrm{tn}}_{\mathrm{hs},t,(d-1)}-\dot{Q}^{\mathrm{tn}}_{\mathrm{hs},t,d}\geq\dot{Q}^{\mathrm{net}}_{\mathrm{hs},t,d}\qquad\forall t,d\tag{4.35}$$

with $\dot{Q}^{\mathrm{tn}}_{\mathrm{hs},t,k,(d-1)}$ the excess heat transferred from interval $d-1$ to interval d and $\dot{Q}^{\mathrm{net}}_{\mathrm{hs},t,d}$ the heat required by the heating network in interval d.

Energy cascade between the heating network and the buildings for each temperature interval:

$$\dot{Q}^{\mathrm{net}}_{\mathrm{hs},t,d}+\sum_{k}\dot{Q}^{\mathrm{nb}}_{\mathrm{hs},t,k,(d-1)}-\sum_{k}\dot{Q}^{\mathrm{nb}}_{\mathrm{hs},t,k,d}\geq\sum_{k}(\dot{Q}^{\mathrm{req}}_{H,t,k,d}+\dot{Q}^{\mathrm{req}}_{HW,t,k,d})\qquad\forall t,d\tag{4.36}$$

with $\sum\limits_{k}\dot{Q}^{\mathrm{nb}}_{\mathrm{hs},t,k,(d-1)}$ is the heat from the heating network transferred from interval $d-1$ to interval d, and $\sum\limits_{k}(\dot{Q}^{\mathrm{req}}_{H,t,k,d}+\dot{Q}^{\mathrm{req}}_{HW,t,k,d})$ the sum of all the heating and hot water requirements of the district in interval d.

The link between the energy cascade defined in Equation 4.35 and the energy cascade defined in Equation 4.36 is ensured by the term $\dot{Q}^{\mathrm{net}}_{\mathrm{hs},t,d}$ and its corresponding mass flow rate (given by Equation 4.28 and/or 4.29), which remains constant for all temperature intervals.

Energy cascade between the district cooling technologies and the cooling network for each temperature interval:

$$\sum_{ct}\sum_{k}\dot{Q}^{\mathrm{tech}}_{ct,t,k,d}+\dot{Q}^{\mathrm{tn}}_{\mathrm{cs},t,(d-1)}-\dot{Q}^{\mathrm{tn}}_{\mathrm{cs},t,d}\geq\dot{Q}^{\mathrm{net}}_{\mathrm{cs},t,d}\qquad\forall t,d\tag{4.37}$$

Energy cascade between the cooling network and the buildings for each temperature interval:

$$\dot{Q}^{\mathrm{net}}_{\mathrm{cs},t,d}+\sum_{k}\dot{Q}^{\mathrm{nb}}_{\mathrm{cn},t,k,(d-1)}-\sum_{k}\dot{Q}^{\mathrm{nb}}_{\mathrm{cn},t,k,d}\geq\sum_{k}\dot{Q}^{\mathrm{req}}_{C,t,d,k}\qquad\forall t,d\tag{4.38}$$

Like for the heating network, the link between the energy cascade defined in Equation 4.37 and the energy cascade defined in Equation 4.38 is ensured by the term $\dot{Q}^{\mathrm{net}}_{\mathrm{cs},t,d}$ and its corresponding mass flow rate (given by Equation 4.30 and/or 4.31), which remains constant for all temperature intervals.

Electricity balances

Unlike the heating and cooling networks, for the electricity the distribution network is assumed to be already existing, and all the electricity is distributed from the

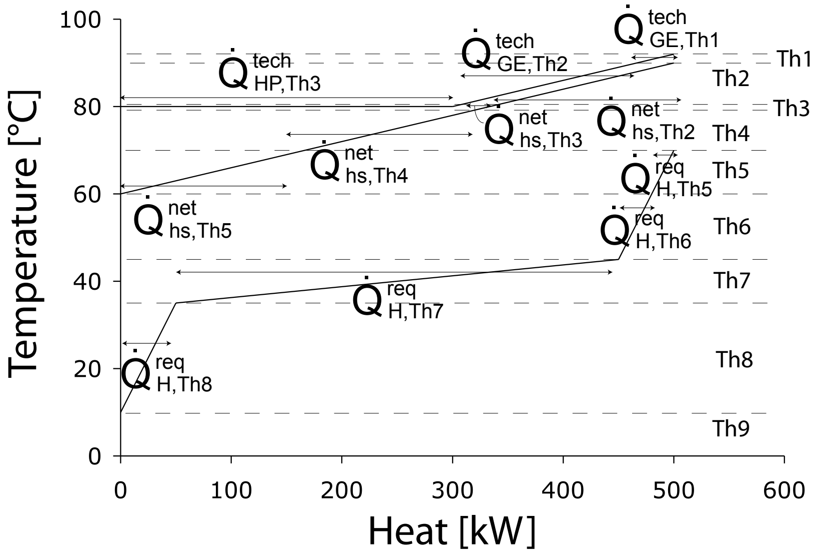

Figure 4.6: Energy terms appearing in the constraints of the energy cascades, with Th1..Th9 the temperature intervals (the indexes t and k have been omitted to avoid overloading the figure)

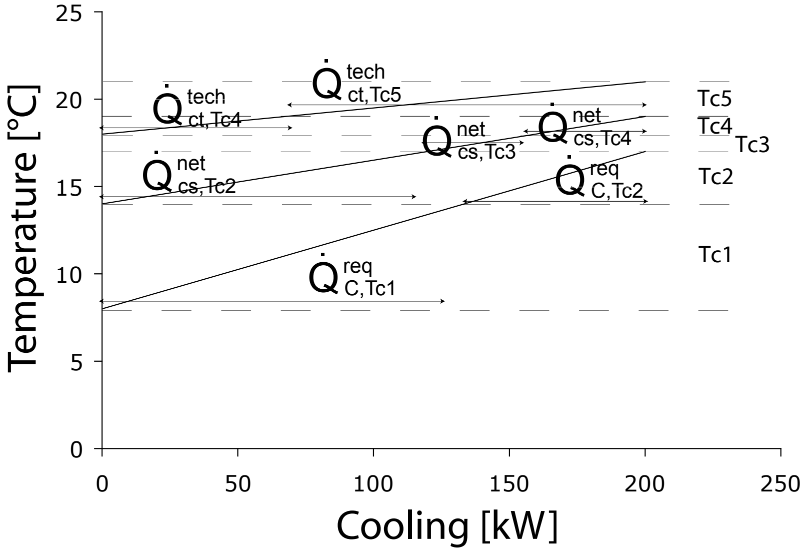

Figure 4.7: Energy terms appearing in the constraints of the cooling cascades, with Tc1..Tc5 the temperature intervals (the indexes t and k have been omitted to avoid overloading the figure)

district energy conversion technologies to the consumers via the grid. However, because the grid experiences some losses (the grid efficiency, ϵ^{grid}, is assumed to reach 90%[11]), not all the electricity generated is available to meet the requirements of the district, namely the consumption of the buildings together with the possible consumption of the different energy conversion technologies if requested (for instance heat pumps or chillers). Since no individual back-up technology has been defined that could generate electricity locally at a given node, and since the distribution network does not need to be designed (unlike for the heating and cooling networks), the energy balance given by the following Equation 4.39 is sufficient to describe the system. This balance link the electricity consumed ($\dot{E}_{t,k}^{\text{cons}}$, $\dot{E}_t^{\text{pump}}$, $\dot{E}_{t,k}^{\text{aw}}$, $\dot{E}_{t,k}^{\text{ww}}$, $\dot{E}_{t,k}^{\text{chiller}}$ and $\dot{E}_t^{\text{loss}}$), sold to the grid ($\dot{E}_t^{\text{sold}}$)[12] and provide to the district by the district technologies ($\dot{E}_t^{\text{grid}}$) or the grid ($\dot{E}_t^{\text{grid}}$):

$$\sum_k \dot{E}_{t,k}^{\text{cons}} + \dot{E}_t^{\text{pump}} + \sum_k (\dot{E}_{t,k}^{\text{aw}} + \dot{E}_{t,k}^{\text{ww}} + \dot{E}_{t,k}^{\text{chiller}}) + \dot{E}_t^{\text{loss}} + \dot{E}_t^{\text{sold}} = \dot{E}_t^{\text{grid}} + \sum_{ht} \dot{E}_{ht,t,k}^{\text{tech}} \qquad \forall t \tag{4.39}$$

Electricity generated by the district technologies:

$$\dot{E}_{ht,t,k}^{\text{tech}} = \frac{\dot{Q}_{ht,t,k}^{\text{tech}}}{\epsilon_{\text{th}}^{ht}} \cdot \epsilon_{\text{el}}^{ht} \qquad \forall ht, t, k \tag{4.40}$$

If a district energy conversion technology requires electricity (such as a heat pump), its electric efficiency has been computed such that $\epsilon_{\text{el}}^{ht} < 0$. Therefore $\dot{E}_{ht,t,k}^{\text{tech}}$ is also < 0[13].

Electricity losses:

$$\dot{E}_t^{\text{loss}} = (1 - \epsilon^{\text{grid}}) \cdot \sum_{ht} \dot{E}_{ht,t}^{\text{exp}} \qquad \forall t \tag{4.41}$$

Electricity required for the individual back-up water/water heat pump(s):

$$\dot{E}_{t,k}^{\text{ww}} = \frac{\dot{Q}_{t,k}^{\text{ww}}}{COP_{t,k}^{\text{ww}}} \qquad \forall t, k \tag{4.42}$$

with $COP_{t,k}^{\text{ww}}$ given by Equation 4.26

---

[11] This value is a pessimistic evaluation since it has been estimated considering the electricity *consumed* in Switzerland. If one considers the electricity consumed *and* the electricity transiting through the country, the following values can be considered as realistic for the losses: international high voltage transportation and distribution network (380 kVolt): 6-7%, national high voltage transportation network (220 kVolt): 2-3%, regional medium voltage (125-150 kVolt) and urban low voltage transportation and distribution network (11-50 kVolt): 8-10% [18].

[12] If the district energy conversion technologies generate *more* electricity than what is needed in the district, the excess electricity can be sold to the company managing the grid.

[13] For instance, if a district heat pump has a COP of 3, $\epsilon_{\text{el}}^{ht} = -0.33$ and $\epsilon_{\text{th}}^{ht} = 1$. Therefore, $\dot{E}_{ht,t,k}^{\text{tech}} = -0.33 \cdot \frac{\dot{Q}_{ht,t,k}^{\text{tech}}}{\epsilon_{\text{th}}^{ht}}$

Electricity required for the individual back-up air/water heat pump(s):

$$\dot{E}^{\text{aw}}_{t,k} = \frac{\dot{Q}^{\text{aw}}_{t,k}}{COP^{\text{aw}}_{t,k}} \qquad \forall t, k \tag{4.43}$$

with:

$$COP^{\text{aw}}_{t,k} = \eta^{hp} \cdot \frac{T_{Hs,t,k} + \Delta T}{T_{Hs,t,k} - T^{\text{atm}}} \forall t, k \tag{4.44}$$

Electricity required for the individual back-up chiller(s):

$$\dot{E}^{\text{chiller}}_{t,k} = \frac{\dot{Q}^{\text{chiller}}_{t,k}}{COP^{\text{chiller}}_{t,k} - 1} \qquad \forall t, k \tag{4.45}$$

Electricity required by the network circulation pumps:

$$\dot{E}^{\text{pump}}_{t} = \frac{\left\{ \sum_{i,j} \left(\dot{M}_{\text{hs},t,i,j} + \dot{M}_{\text{hr},t,i,j} + \dot{M}_{\text{cs},t,i,j} + \dot{M}_{\text{cr},t,i,j} \right) \cdot Dist_{i,j} \right\} \cdot p^{\text{drop}}_{t}}{\rho} \qquad \forall t \tag{4.46}$$

Mass balances

Mass balances are defined at each node for both the supply and the return networks. They link the mass flow rate of water leaving the node (left hand side of the = sign in Equations 4.47 and 4.48), with the mass flow rate of water arriving at the node, flowing through the building located at the node, and coming from the building at node k if a district energy conversion technology is located at that node (right hand side of the = sign).

Heating supply network:

$$\sum_{(k,j)} \dot{M}_{\text{hs},t,k,j} = \sum_{(i,k)} \dot{M}_{\text{hs},t,i,k} - (\dot{M}^{\text{build}}_{\text{hn},t,k} + \dot{M}^{\text{hn\_ww}}_{\text{hn},t,k}) + \dot{M}^{\text{tech}}_{\text{hn},t,k} \qquad \forall t, k \tag{4.47}$$

Cooling supply network:

$$\sum_{(k,j)} \dot{M}_{\text{cs},t,k,j} = \sum_{(i,k)} \dot{M}_{\text{cs},t,i,k} - \dot{M}^{\text{build}}_{\text{cn},t,k} + \dot{M}^{\text{tech}}_{\text{cn},t,k} \qquad \forall t, k \tag{4.48}$$

(Symmetric equations are defined for the return pipes in each network.)

Connections of nodes and implementation/location of the technologies

The following constraints have been defined for the design of the network configuration (connections), and for the location of the district and individual back-up energy conversion technologies.

Network configuration

Equation 4.49 and 4.50 define the existence of a connection between nodes i and j for networks hs and cs if energy (therefore water) flows from i to j (explanations for $\dot{M}^{\text{ub}}_{\text{hs}}$ and $\dot{M}^{\text{ub}}_{\text{cs}}$ are given in Section 4.5.3)[14]:

$$X_{\text{hs},i,j} \cdot \dot{M}^{\text{ub}}_{\text{hs}} \geq \dot{M}_{\text{hs},t,i,j} \qquad \forall t, i, j \tag{4.49}$$

$$X_{\text{cs},i,j} \cdot \dot{M}^{\text{ub}}_{\text{cs}} \geq \dot{M}_{\text{cs},t,i,j} \qquad \forall t, i, j \tag{4.50}$$

Equations 4.51 ensures that if a connection is implemented from node i to j in the heating supply network (hs) a connection is implemented from j to i in the heating return network (hr). The same is valid for the cooling network (between the supply cs and the return cr, Equation 4.52). Equation 4.53 ensures that the heating and the cooling network run parallel to each other.

$$X_{\text{hs},i,j} = X_{\text{hr},j,i} \forall i, j \tag{4.51}$$

$$X_{\text{cs},i,j} = X_{\text{cr},j,i} \forall i, j \tag{4.52}$$

$$X_{\text{hs},i,j} = X_{\text{cs},i,j} \forall i, j \tag{4.53}$$

District energy conversion technologies

Equations 4.54 and 4.55 for the district heating technologies and 4.57 and 4.58 for the district cooling technologies define the node where a district technology will be implemented ($X_{ht,k}$ respectively $X_{ct,k}$), and ensure that if the technology is operated ($x_{ht,t}$ and $x_{ct,t}$), the heating or cooling generated by the district technology remains between the design load of the technology and the minimum technically acceptable part load (κ_{ht} and κ_{ct}). Y^{tech}_k defines the eligibility or not of a node to host a technology and is defined in the structuring phase.

Heating technologies:

$$\dot{Q}^{\text{tech}}_{ht,t,k} \leq x_{ht,t} \cdot X_{ht,k} \cdot Y^{\text{tech}}_k \cdot S_{ht} \qquad \forall ht, t, k \tag{4.54}$$

$$\dot{Q}^{\text{tech}}_{ht,t,k} \geq x_{ht,t} \cdot X_{ht,k} \cdot Y^{\text{tech}}_k \cdot S_{ht} \cdot \kappa_{ht} \qquad \forall ht, t, k \tag{4.55}$$

$$\sum_k X_{ht,k} \leq 1 \qquad \forall ht \tag{4.56}$$

Cooling technologies:

$$\dot{Q}^{\text{tech}}_{ct,t,k} \leq x_{ct,t} \cdot X_{ct,k} \cdot Y^{\text{tech}}_k \cdot S_{ct} \qquad \forall ct, t, k \tag{4.57}$$

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[14] Note that the binary variables are no indexed over the periods t since the final layout of the network is the same for all periods.

$$\dot{Q}^{\text{tech}}_{ct,t,k} \geq x_{ct,t} \cdot X_{ct,k} \cdot Y^{\text{tech}}_{k} \cdot S_{ct} \cdot \kappa_{ct} \qquad \forall ct, t \tag{4.58}$$

$$\sum_{k} X_{ct,k} \leq 1 \qquad \forall ct \tag{4.59}$$

Sizes of the individual back-up energy conversion technologies

The following constraints are defined for each type of individual back-up energy conversion technology (air/water heat pumps, water/water heat pumps, boilers and chillers)[15]. Constraints 4.60, 4.63, 4.66 and 4.69 define the size, S, of the required individual back-up energy conversion technologies, and Constraints 4.61, 4.64, 4.67 and 4.70, as well as Constraints 4.62, 4.65, 4.68 and 4.71 the nodes on which they are implemented. Regarding electricity, no individual back-up energy conversion technologies are available. Any electricity requirements that cannot be satisfied by the district energy conversion technologies are met by purchasing electricity from the grid. (Note that in the following equations the index H refers to the sum of the heating *and* hot water requirements that would be met by the individual back-up technology.)

Air/water heat pump:

$$\dot{Q}^{\text{aw}}_{t,k} \leq S^{\text{aw}}_{k} \qquad \forall t, k \tag{4.60}$$

$$X^{\text{aw}}_{k} \cdot \dot{Q}^{\max}_{H,k} \geq S^{\text{aw}}_{k} \qquad \forall k \tag{4.61}$$

$$X^{\text{aw}}_{k} \cdot \dot{Q}^{\min}_{H,k} \leq S^{\text{aw}}_{k} \qquad \forall k \tag{4.62}$$

Water/water heat pump:

$$\dot{Q}^{\text{ww}}_{t,k} \leq S^{\text{ww}}_{k} \qquad \forall t, k \tag{4.63}$$

$$X^{\text{ww}}_{k} \cdot \dot{Q}^{\max}_{H,k} \geq S^{\text{ww}}_{k} \qquad \forall k \tag{4.64}$$

$$X^{\text{ww}}_{k} \cdot \dot{Q}^{\min}_{H,k} \leq S^{\text{ww}}_{k} \qquad \forall k \tag{4.65}$$

Boiler:

$$\dot{Q}^{\text{boiler}}_{t,k} \leq S^{\text{boiler}}_{k} \qquad \forall t, k \tag{4.66}$$

$$X^{\text{boiler}}_{k} \cdot \dot{Q}^{\max}_{H,k} \geq S^{\text{boiler}}_{k} \qquad \forall k \tag{4.67}$$

$$X^{\text{boiler}}_{k} \cdot \dot{Q}^{\min}_{H,k} \leq S^{\text{boiler}}_{k} \qquad \forall k \tag{4.68}$$

Chiller:

$$\dot{Q}^{\text{chiller}}_{t,k} \leq S^{\text{chiller}}_{k} \qquad \forall t, k \tag{4.69}$$

$$X^{\text{chiller}}_{k} \cdot \dot{Q}^{\max}_{H,k} \geq S^{\text{chiller}}_{k} \qquad \forall k \tag{4.70}$$

$$X^{\text{chiller}}_{k} \cdot \dot{Q}^{\min}_{H,k} \leq S^{\text{chiller}}_{k} \qquad \forall k \tag{4.71}$$

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[15] Remember that beside ensuring the physical satisfaction of all the energy requirements, the back-up technologies guarantee, mathematically, the convergence of the slave optimization.

4.4.4 Costing and CO$_2$ emission functions

The costing functions implemented in the slave optimization include:

1. the investment costs of the pipes of the distribution networks, the circulation pumps, the heat exchangers between the networks and the buildings, and the individual back-up energy conversion technologies[16],
2. the operating costs (natural gas, electricity from the grid and oil for the boilers),
3. the incomes from the electricity sales.

ANNUAL INVESTMENT COSTS FOR THE PIPES

To compute the investment costs for the pipes, the fixed costs are charged if a heating and/or cooling pipe is requested between two nodes ($X_{\mathrm{hs},i,j} = 1$ and/or $X_{\mathrm{cs},i,j} = 1$), but not yet existing ($Y^{\mathrm{pipe}}_{\mathrm{hs},i,j} = 0$ and/or $Y^{\mathrm{pipe}}_{\mathrm{cs},i,j} = 0$). If both heating and cooling pipes are requested, the fixed costs are charged only once.

$$\begin{aligned} C^{\mathrm{pipes}} &= \frac{Ms^{\mathrm{pipe}}}{1306.6} \cdot (1 + Fm^{\mathrm{pipe}}) \cdot An^{\mathrm{pipe}} \cdot \sum_{(i,j)} Dist_{i,j} \cdot \\ &\quad ((X_{i,j} \cdot C^{\mathrm{pipe}}_{fix}) + ((A_{\mathrm{hs},i,j} \cdot c^{\mathrm{pipe}}_{prop}) \cdot (1 - Y^{\mathrm{pipe}}_{\mathrm{hs},i,j}) \cdot X_{\mathrm{hs},i,j}) + \\ &\quad ((A_{\mathrm{cs},i,j} \cdot c^{\mathrm{pipe}}_{prop}) \cdot (1 - Y^{\mathrm{pipe}}_{\mathrm{cs},i,j}) \cdot X_{\mathrm{cs},i,j}) \end{aligned} \tag{4.72}$$

with:

$$X_{i,j} \geq (X_{\mathrm{hs},i,j} \cdot (1 - Y^{\mathrm{pipe}}_{\mathrm{hs},i,j})) \qquad \forall i, j \tag{4.73}$$

and:

$$X_{i,j} \geq (X_{\mathrm{cs},i,j} \cdot (1 - Y^{\mathrm{pipe}}_{\mathrm{cs},i,j})) \qquad \forall i, j \tag{4.74}$$

to ensure that the fixed costs for the pipes only accrue if a heating and/or cooling pipe is/are required and not already existing.

Moreover:

$$A_{\mathrm{hs},i,j} = \frac{\max_t \dot{M}_{\mathrm{hs},t,i,j}}{v \cdot \rho} \qquad A_{\mathrm{cs},i,j} = \frac{\max_t \dot{M}_{\mathrm{cs},t,i,j}}{v \cdot \rho} \qquad \forall i, j$$

ANNUAL INVESTMENT COSTS FOR THE PUMPS

Heating network:

$$\begin{aligned} C^{\mathrm{pump}} &= \frac{Ms^{\mathrm{pump}}}{1306.6} \cdot (1 + Fm^{\mathrm{pump}}) \cdot An^{\mathrm{pump}} \cdot \\ &\quad ((X^{\mathrm{hn}} \cdot C^{\mathrm{pump}}_{fix} + S^{\mathrm{pump}}_{\mathrm{hn}} \cdot c^{\mathrm{pump}}_{prop}) + \\ &\quad (X^{\mathrm{cn}} \cdot C^{\mathrm{pump}}_{fix} + S^{\mathrm{pump}}_{\mathrm{cn}} \cdot c^{\mathrm{pump}}_{prop})) \end{aligned} \tag{4.75}$$

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[16] The investment costs for the district energy conversion technologies being computed in the thermo-economic models (see Figure 2.1).

with:

$$S^{\text{pump}}_{\text{hn}} = \frac{\max\limits_{t} ((\dot{M}_{\text{hs},t,i,j} + \dot{M}_{\text{hr},t,j,i}) \cdot Dist_{i,j} \cdot p^{\text{drop}}_{t})}{\rho} \qquad \forall i, j$$

and

$$S^{\text{pump}}_{\text{hn}} \leq X^{\text{hn}} \cdot (\dot{M}^{\text{ub}}_{\text{hs}} + \dot{M}^{\text{ub}}_{\text{cs}})$$

and symmetrically for the cooling network.

Annual investment costs for the heat exchangers

The investment costs for the heat-exchangers are computed in the data processing routine (Point 2 Paragraph 4.5.1) and result in the following annual investment cost:

$$C^{\text{hex}} = \frac{Ms^{\text{HEX}}}{1306.6} \cdot (1 + Fm^{\text{HEX}}) \cdot An^{\text{HEX}} \cdot \sum_{k} (X^{\text{HEX}}_{\text{hn},k} \cdot C^{\text{HEX\_inv}}_{\text{hs},k} + X^{\text{HEX}}_{\text{cn},k} \cdot C^{\text{HEX\_inv}}_{\text{cs},k}) \tag{4.76}$$

with:

$$\dot{Q}^{\text{build}}_{\text{hs},t,k} + \dot{Q}^{\text{hn\_ww}}_{\text{hs},t,k} \leq X^{\text{HEX}}_{\text{hn},k} \cdot (\dot{Q}^{\text{cons}}_{H,t,k} + \dot{Q}^{\text{cons}}_{HW,t,k}) \qquad \forall t, k$$

and:

$$\dot{Q}^{\text{build}}_{\text{cs},t,k} \leq X^{\text{HEX}}_{\text{cn},k} \cdot \dot{Q}^{\text{cons}}_{C,t,k} \qquad \forall t, k$$

Annual investment costs for the back-up devices

Air/water heat pump:

$$C^{\text{aw}} = \frac{Ms^{\text{aw}}}{1306.6} \cdot (1 + Fm^{\text{aw}}) \cdot An^{\text{aw}} \cdot \sum_{k} \left((X^{\text{aw}}_{k} \cdot C^{\text{aw}}_{fix}) + (S^{\text{aw}}_{k} \cdot c^{\text{aw}}_{prop})\right) \tag{4.77}$$

Water/water heat pump:

$$C^{\text{ww}} = \frac{Ms^{\text{ww}}}{1306.6} \cdot (1 + Fm^{\text{ww}}) \cdot An^{\text{ww}} \cdot \sum_{k} \left((X^{\text{ww}}_{k} \cdot C^{\text{ww}}_{fix}) + (S^{\text{ww}}_{k} \cdot c^{\text{ww}}_{prop})\right) \tag{4.78}$$

Boiler:

$$C^{\text{boiler}} = \frac{Ms^{\text{boiler}}}{1306.6} \cdot (1 + Fm^{\text{boiler}}) \cdot An^{\text{boiler}} \cdot \sum_{k} \left((X^{\text{boiler}}_{k} \cdot C^{\text{boiler}}_{fix}) + (S^{\text{boiler}}_{k} \cdot c^{\text{boiler}}_{prop})\right) \tag{4.79}$$

Chiller:

$$C^{\text{chiller}} = \frac{Ms^{\text{chiller}}}{1306.6} \cdot (1 + Fm^{\text{chiller}}) \cdot An^{\text{chiller}} \cdot \sum_{k} \left((X^{\text{chiller}}_{k} \cdot C^{\text{chiller}}_{fix}) + (S^{\text{chiller}}_{k} \cdot c^{\text{chiller}}_{prop})\right) \tag{4.80}$$

To compute the different annual investment costs listed above, the annuity factor is calculated according to the following equation:

$$An^i = \frac{r^i \cdot (1 + r^i)^{N^i}}{(1 + r^i)^{N^i} - 1} \tag{4.81}$$

Operating costs

Grid costs:

$$C^{\text{grid}} = \sum_t \dot{E}_t^{\text{grid}} \cdot D_t \cdot c^{\text{grid}} \tag{4.82}$$

Natural gas costs:

$$C^{\text{gas}} = \sum_t R_t^{\text{gas}} \cdot D_t \cdot c^{\text{gas}} \tag{4.83}$$

in which:

$$R_t^{\text{gas}} = \sum_{ht} \sum_k \frac{\dot{Q}_{ht,t,k}^{\text{tech}}}{\epsilon_{\text{th}}^{ht}} \tag{4.84}$$

and R_t^{gas} the average hourly gas consumption rate required by all the district energy conversion technologies operated with natural gas (no back-up device is operated with natural gas), and D_t the duration of period t in hours.

Oil costs (only for individual back-up boilers):

$$C^{\text{oil}} = \sum_t R_t^{\text{oil}} \cdot D_t \cdot c^{\text{oil}} \tag{4.85}$$

$$R_t^{\text{oil}} = \sum_k \frac{\dot{Q}_{t,k}^{\text{boiler}}}{\epsilon^{\text{boiler}}} \tag{4.86}$$

with R_t^{oil} the average hourly oil consumption rate required by the boilers, and D_t like above.

Incomes from the electricity sales

$$I^{\text{el}} = \sum_t \dot{E}_t^{\text{sold}} \cdot D_t \cdot b^{\text{grid}} \tag{4.87}$$

where b^{grid} is the price paid by the grid when buying electricity.

CO_2 emissions

The weighting factor for the CO_2 emissions is used in the slave optimization to compute penalty costs related to the CO_2 emissions[17]:

$$C^{CO_2} = \sum_t (R_t^{\text{gas}} \cdot co_2{}^{\text{gas}} + \dot{E}_t^{\text{grid}} \cdot co_2{}^{\text{grid}} + R_t^{\text{oil}} \cdot co_2{}^{\text{oil}}) \cdot D_t \tag{4.88}$$

---

[17] These costs are not passed back to the master optimizer.

4.4.5 Empirical constraints

Empirical constraints are based on the experience of the programmer/engineer and speed up the solution time by reducing the search space appropriately, without excluding the optimal solution. They result from a careful analysis of the problem. The slave optimization includes several such constraints, especially regarding the implementation of the technologies (district technologies and back-up technologies) and the routing of the pipes. Unlike cuts, which are managed directly by the solver (in this case Cplex [25], see Section 3.4 in Chapter 3), or valid inequalities, which are constraints that are formulated by the programmer but which are redundant to other constraints of the problem and don't change the *mathematical* structure of the problem, the addition of empirical constraints do change the purely mathematical structure of the problem since they eliminate feasible integer solutions. However, the eliminated solutions are the ones which are known by the programmer to be sub-optimal solutions. The following empirical constraints have been defined:

CONNECTIONS
If node k is connected to the network, only one heating and/or cooling supply pipe reaches that node. Heating and/or cooling cannot be provided to a node by two different routes.

$$\sum_i X_{\mathrm{hs},i,k} \leq 1 \qquad \forall k \tag{4.89}$$

INDIVIDUAL BACK-UP ENERGY CONVERSION TECHNOLOGIES
No more than one back-up energy conversion technology can be implemented on a given node k to provide heating and hot water (for the cooling requirements there is anyway only one possible back-up technology, so that a constraint such as 4.90 is not necessary):

$$X_k^{\mathrm{aw}} + X_k^{\mathrm{ww}} + X_k^{\mathrm{boiler}} \leq 1 \qquad \forall k \tag{4.90}$$

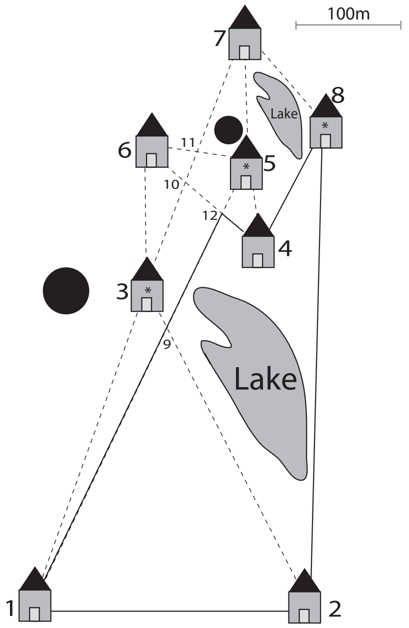
If the node is connected to the network, no air/water heat pump or boiler can be used at this same node:

$$X_k^{\mathrm{aw}} + X_k^{\mathrm{boiler}} + \sum_i X_{\mathrm{hs},i,k} \leq 1 \qquad \forall k \tag{4.91}$$

As mentioned above, none of these equations change anything to the thermo-economics of the problem, but they allow including the experience of the engineer, who knows, for instance, that in the optimal solution there will not be two different individual back-up technologies implemented simultaneously on one node.

ROUTING OF THE PIPES
The following constraint prevents the slave optimizer from computing solutions including the cycles listed in the set *cycle*:

$$\sum_{i \in cycle[c]} X_{i,next(i)} \leq card(cycle[c]) - 1; \tag{4.92}$$



Cycle	Connected nodes
1	1-9-2
2	3-9-1
3	5-11-10-3-9-1-2-8-7
4	11-10-3-6
5	5-4-12-10-11
6	5-11-10-12-4-8-7
7	5-12-10-11
8	11-6-10
9	5-7-11
10	10-3-9-12
11	4-8-7-5
12	1-9-12-4-8-2

Figure 4.8: Cycles in a network

No optimal solution indeed will contain cycles in the network. It is not advisable however to list *all* the possible cycles of the district, as the increase in constraints can become counter-productive. To the experience of the author, it is sufficient to define the elementary meshes (like mesh 1-2-9-1 in Figure 4.8), together with a few combinations of elementary meshes (like mesh 1-9-12-4-8-2-1 which is a combination of mesh 1-2-9-1 and mesh 2-9-12-4-8-2), to improve considerably the resolution time. For instance for the test case imagined on purpose to develop the method and shown in Figure 4.8, the cycles listed in the table next to the figure have been defined[18].

4.5 Data processing routine

As already explained, the evolutionary algorithm used in the master optimization builds a genome, the performance of which is computed, and the result evaluated before creating the next genome. To compute its performances, the genome is passed over to the slave optimization via the thermo-economic models from the district technology data base and the data processing routine. According to the values given by the master optimization to the decision variables, this data processing routine performs the following different tasks:

1. It computes the inputs for the slave optimization. Note that because of the decomposition of the problem, the *decision variables* optimized in the master

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[18] Note that the cycles mentioned here do not relate to the cycles which are implemented in district energy systems to guarantee the security of supply in case one pipe is out of order. These latter cycles shall be taken into account in a more detailed modelling phase, once the basic layout of the district energy system has been established.

optimization become *inputs* or *parameters* in the slave optimization.

2. It performs various controls on the decision variables of the master optimization, to check for inconsistencies or unreasonable values.
3. It defines the upper and lower bounds of the continuous decision variables of the slave optimization, that can be derived from the values given by the master optimization.

If the computation of the inputs or parameters (Item 1 above) is compulsory for the slave optimization compute a solution, the controls performed on the decision variables of the master optimization (Item 2) and the definition of the bounds (Item 3) basically aim at improving the resolution time of the slave optimization.

4.5.1 Inputs and parameters

Given the values of the decision variables belonging to the master set of decision variables, the data processing routine processes the following inputs for the slave optimization: temperature intervals with upper and lower bounds for the energy cascades, heat exchanger surfaces and costs, average specific heat losses, average specific pressure losses. The way the data processing routine does this is explained hereunder:

1. TEMPERATURE INTERVALS WITH UPPER AND LOWER BOUNDS FOR THE ENERGY CASCADES
   The energy cascade of a thermodynamic system is defined by the sum of all the energy balances, defined for each temperature interval appearing in the system, between the hot and the cold streams (Equations 4.35 to 4.38). Such an energy balance around one temperature interval is shown in Figure 4.9. Graphically, a energy cascade is represented by a hot composite curve and a cold composite curve. The hot composite curve aggregates all fluids in the analysed system that need to be cooled down (or have a heating potential), and the cold composite curve aggregates all fluids in the analysed system that need to be heated up (or have a cooling potential). Examples of such systems of hot and cold composite curves have already been shown in Figures 4.6 and 4.7[19]. To solve the heat cascades algebraically with the Equations 4.35 to 4.38, the shifted (corrected) temperatures are used for each hot and cold stream. This means that the fluids that are cooled down are given with their temperature shifted down by half the minimum temperature difference, and the fluids that are heated up are given by their temperature shifted up by half

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[19] Unlike the energy cascades computed when analysing energy consuming systems (such as chemical plants for instance), and which aim at finding the minimal energy requirements that have to be satisfied by an *external* energy source for the chemical process to be performed, the energy cascades computed in the DESD(OP)^2 ensure that the energy balances are satisfied in each temperature interval. No external energy source, other than the district and the individual back-up energy conversion technologies, is considered in the present problem.

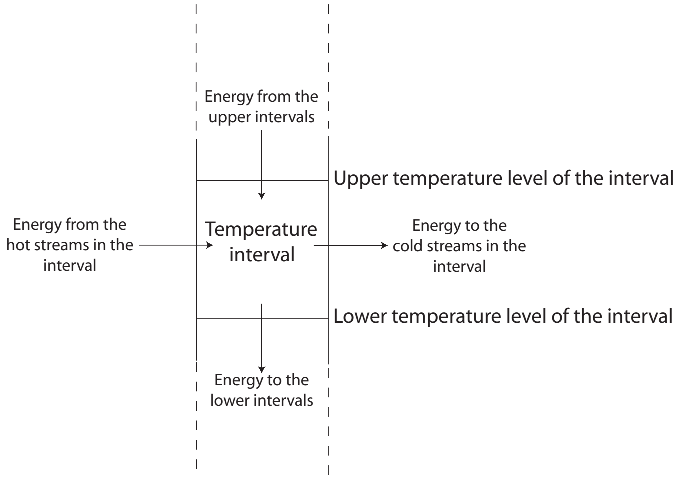

Figure 4.9: Energy balance around a temperature interval

the minimum temperature difference[20].

The upper and lower bounds of each temperature interval required to compute the heat cascades can be defined in the data processing routine, since all the temperature levels contributing to the heat cascades are known at this stage. These include:

- the heating or cooling delivery temperature(s) of the district energy conversion technologies,
- the supply and return temperatures of the networks,
- the temperature levels of the thermal energy requirements of the buildings in the district.

2. Heat exchanger surfaces and costs

Knowing the temperature levels for the heating, hot water and cooling requirements in the buildings, as well as the supply and return temperatures of the networks, the area and the costs of the required heat exchangers between the networks and the buildings can be computed for each building k, considering an average overall heat exchange coefficient of 800 [W/(m^2*K)] [26]. The costs are computed using the following correlation [26] (shown here for heating), based on the area $A^{HEX}_{\text{hs},k}$ of the heat exchanger located at node k (if building k is connected to the cooling network, analogous costs are computed for the heat exchanger between the cooling and the building):

$$C^{\text{HEX\_inv}}_{\text{hs},k} = 3364 \cdot \left(\frac{A^{HEX}_{\text{hs},k}}{5.5} \right)^{0.6} \tag{4.93}$$

---

[20] This ensures that a cold stream that needs to be heated up from 70°C to 90°C for instance, cannot receive energy from a fluid that would need to be cooled down from 90°C to 70°C, by the same amount of energy.

These costs are passed over to the slave optimizer in order to be considered when optimizing the network configuration and the buildings to be connected.

3. HEAT LOSSES
 The data processing routine computes the *periodic* average specific heat losses in [kW/m] corresponding to the heating supply temperature selected by the master optimizer, assuming a heat transfer coefficient of $K = 0.203$ W/(mK) [77]. This is done by considering first the mass flow rate of water required to meet the sum of all the heating and hot water requirements of the entire district during the given period (in other words the *maximum* possible mass flow rate), and second the mass flow rate required to meet the minimum, different 0, heating or hot water requirement of the district during the same period (in other words the *minimum* possible mass flow rate). These two flow rates can be computed since the supply and return temperatures of the network are known. The periodic average between the specific heat losses for the maximum and for the minimum mass flow rates is given as a parameter to the slave optimization. For both mass flow rates, and for each period, the heat losses are computed with the following general correlations [77] (with $T_{\text{hs},t}$ the supply temperature of the heating network, $T_{\text{end},t}$ the temperature at the end of the pipe, T_g the ground temperature, L the length of the pipe, and $\dot{M}$ the mass flow rate):

$$\dot{q}_t^{\text{loss}} = (T_{\text{hs},t} - T_{\text{end},t}) \cdot cp_{H_2O}^{\text{liq}} \cdot \dot{M} \quad [\text{kW/m}] \tag{4.94}$$

 with:

$$T_{\text{end},t} = T_g + (T_{\text{hs},t} - T_g) \cdot \exp\left(\frac{K \cdot L}{\dot{M} \cdot cp_{H_2O}^{\text{liq}}}\right) \tag{4.95}$$

 To compute the specific heat losses, a length of 1 meter is chosen. Remember that the heat losses for the cooling network are considered to be negligible, due to the relatively small temperature difference between the supply pipes and the surroundings as compared to the heating network.

4. PRESSURE DROP
 The pressure drop is needed to compute the pumping power. The specific pressure drop [Pa/m] is approximated in the same way as the heat losses. A diameter d is computed for each period for the maximum and the minimum mass flow rates for both heating and cooling. The corresponding specific pressure drop for a length of $L = 1$ meter and a velocity in the pipes of $v = 4$m/s are computed according to Equation 4.96, in which λ is the friction coefficient in the pipes ($\lambda = 0.02$). The average between the maximum and the minimum pressure drops for both heating and cooling is passed over to the slave optimization as a parameter.

$$p_t^{\text{drop}} = 0.5 \cdot \rho \cdot v^2 \cdot \left(\frac{\lambda \cdot L}{d}\right) \quad [\text{Pa/m}] \tag{4.96}$$

4.5.2 Inconsistencies and unreasonable values

The data processing routine checks the values given to the master set of decision variables to check the following issues: inconsistencies between values of the master set of decision variables, unreasonable values given to some variables of the master set of decision variables, and inconsistencies between the variables optimized by the master optimization and the outputs resulting from the structuring phase. The way the data processing routine does this is explained hereunder:

1. Inconsistencies among variables optimized by the master optimization
   An example of inconsistency is, for instance, when the master optimizer defines a condenser temperature for a heat pump that is below the return temperature of the heating network, making the heat pump useless. In this case, the data processing routine doesn't pass the heat pump to the slave optimization, thus reducing its search space and avoiding the iterations that would be necessary in the slave optimization to find out that the heat pump is useless. The annual investment cost of the heat pump is nonetheless taken into account in the objective function of the master optimization. Hence the technology induces investment costs, but does not provide any useful energy, thus discouraging the master optimizer from choosing it. Such controls can be included for any type of district energy conversion technology, according to the specificities of the technology.

2. Unreasonable values among the variables optimized by the master optimization
   Unreasonable values among the variables optimized by the master optimization affect essentially the total size of the district energy conversion technologies selected by the master optimization. Theoretically, the master optimization can choose any combination of type and size of district energy conversion technologies from the list of possible technologies given for the district. Practically, the experience has shown, that, for instance, if the total size of the district energy conversion technologies selected by the master optimization, exceeded the maximum overall heating and hot water requirements by more than an arbitrary factor (greater than 1), the resolution time of the slave optimization could explode from 2-3 minutes to over an hour[21], without any improvement in the value of the objective function in the slave optimization. The same observation was done for the cooling requirements. The reason for this is the excessive search space resulting from ill-suited technologies. Therefore, the data processing routine needs to check that the total size of the technologies passed over to the slave optimization is not too large. (See Appendix A.1 for more details)

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[21] These time estimations refer to computers featuring Intel Pentium4 processors, 2'800 MHz, with 2 GB memory

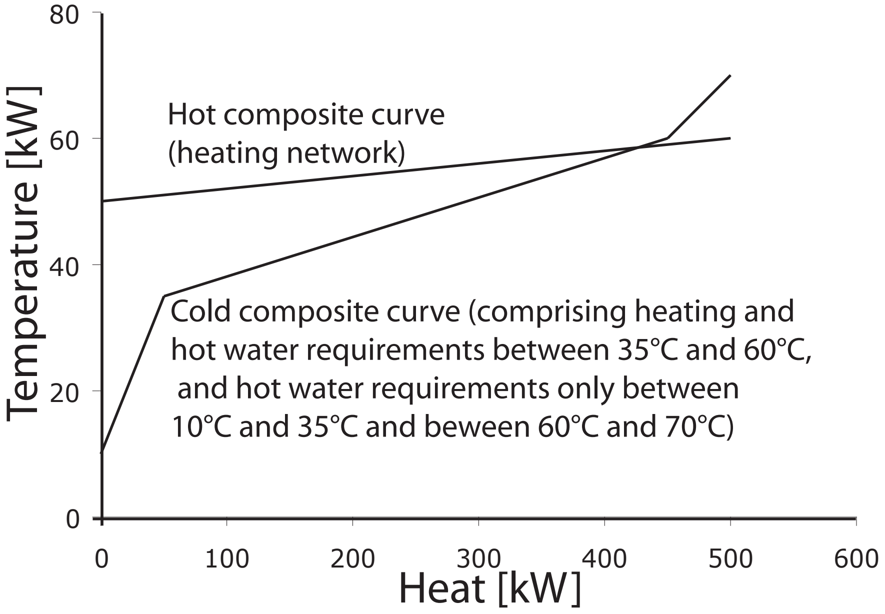

Figure 4.10: Hot and cold composite curves for a system having a heating supply temperature below the required temperature level of the building

3. Inconsistencies between the variables optimized by the master optimization and the outputs from the structuring phase
Inconsistencies between the variables optimized by the master optimization and the outputs resulting from the structuring phase are, above all, related to the temperature levels. Let us assume that the master optimization selects a supply temperature for the heating network of 60°C and a return temperature of 50°C. Let us further assume that some buildings in the district require heat between 10°C and 70°C for their heating and hot water requirements, with a minimum temperature difference of 2°C between the heating network and the hydronic circuit of the buildings (see Figure 4.10). For these buildings, the supply temperature of the network should therefore be at least equal to: $70+2 = 72$°C, which is 2°C higher than the supply temperature of the heating network. To solve this problem, the slave optimization will have to implement boilers (the required temperature of 72°C preventing from using individual back-up heat pumps). The data processing routine therefore defines a variable that is set to 1, if the supply temperature of the network is above the supply temperature of the hydronic circuit of the building plus the minimum temperature difference, *and*, if the return temperature of the network is above the return temperature of the hydronic circuit of the building plus the minimum temperature difference. In all other cases this variable is set to 0. This variable is then included in the constraints of the slave optimization, and if the value of the variable equals 0, the slave optimizer doesn't try to connect the building directly to the network, thus saving iterations.

4.5.3 Upper and lower bounds

The resolution time of the slave optimization to compute binary variables is improved if the bounds on the continuous variables are as tight as possible, without however excluding the optimal solution from the search space. It is indeed wiser to program for example, for the heating supply network:

$$X_{\mathrm{hs}i,j} \cdot \dot{M}_{\mathrm{hs}}^{\mathrm{ub}} \geq \dot{M}_{\mathrm{hs},t,i,j} \tag{4.97}$$

$$X_{\mathrm{hs}i,j} \cdot \dot{M}_{\mathrm{hs}}^{\mathrm{lb}} \leq \dot{M}_{\mathrm{hs}t,i,j} \tag{4.98}$$

instead of the simpler version:

$$X_{\mathrm{hs}i,j} \cdot \boldsymbol{M} \geq \dot{M}_{\mathrm{hs}t,i,j} \tag{4.99}$$

where $\boldsymbol{M}$ is an arbitrarily large value (the same being valid of course for the cooling networks). Very often, experience has shown that Equation 4.97 alone will already bring considerable improvement compared to Equation 4.99, if $\dot{M}_{\mathrm{hs}}^{\mathrm{ub}}$ is defined appropriately. (See Appendix A.2 for further details.)

Depending on the analysed district, the number of nodes, the number of possible connections, the number of time periods,... adding up the improvements explained in Sections 4.5.2 and 4.5.3 above, results in a slave optimization lasting over an hour (if no appropriate data processing is performed), to less than a minute (with appropriate data processing). Considering that the master optimizer runs several thousands of iterations to converge, the obtained time benefit is considerable.

4.6 Assumptions adopted in the optimization phase

The general assumptions considered in the optimization phase are listed hereunder:

1. The analysed districts are flat and no consideration is given to the differences in altitude.
2. All heat-exchangers are counter-flow heat-exchangers.
3. For the individual back-up heat pumps, the condenser temperature has been chosen in function of the hot water requirements (regardless if the heat pump meets heating or hot water requirements). This assumption penalizes especially low temperature heating buildings and should therefore be refined in a more detailed approach.
4. If any excess electricity is generated by the district energy conversion technologies, it can be decided from case to case, by the decision maker, whether this electricity shall be sold to the grid or not (see results Section 5.3.7).
5. If any excess heating or cooling is generated by the district energy conversion technologies, this energy is lost to the surroundings.

6. No storage is being considered.
7. Heat losses in the pipes are considered for the heating network but neglected for the cooling network, due to the relatively small temperature difference between the supply pipes and the surroundings as compared to the heating network.

4.7 Conclusion

In this chapter, the optimization phase is explained in greater details. The chapter shows all equations that enable to solve the DESD(OP)^2 problem, which is actually a combination of two well known types of problems, namely the multi-period optimization problems (see [65] for an example of such problems) and the network problems. The objective function, constraints, parameters and decision variables for each of the optimizations (master and slave) are given. Besides, it is shown how the resolution time of the slave optimization could be improved by reducing the search space appropriately, thus reducing the number of iterations needed in the salve optimization to compute a solution.

Chapter 5

Test case application

5.1 Introduction

In this chapter, the method to solve the DESD(OP)^2 problem[1] is demonstrated by means of a virtual test case developed for this purpose. The district and its maximum requirements for each energy service is shown on Figure 5.1. The method will be applied and discussed step by step following the different phases as explained in Chapter 2 and shown on Figure 2.1. This chapter emphasizes the optimization phase and shows the results that can be obtained, as well as a few sensitivity analysis to demonstrate the abilities of the slave optimization. The following chapter, dealing with a real case in the Canton of Geneva, will likewise present results from the optimization phase, but also show how missing information can be completed in the structuring phase.

5.2 Description of the test case and structuring of the information

The goal of the method described in the preceding chapters and demonstrated here, is to provide a tool to help answering following question: Given a district with its buildings, how can the energy requirements of this district, in terms of heating, hot water, cooling and electricity, be satisfied, thus considering the minimization of the yearly CO_2 emissions and costs? The virtual district dedicated to develop the method (Figure 5.1) is supposed to be new, such that no equipment is existing beforehand, except for the electricity grid which is assumed to be available. Note that the dashed lines in Figure 5.1 show the connections which are allowed between buildings and/or crossings (nodes), and do by no means suggest the presence of already existing pipes.

According to the method, the following information is gathered and structured:

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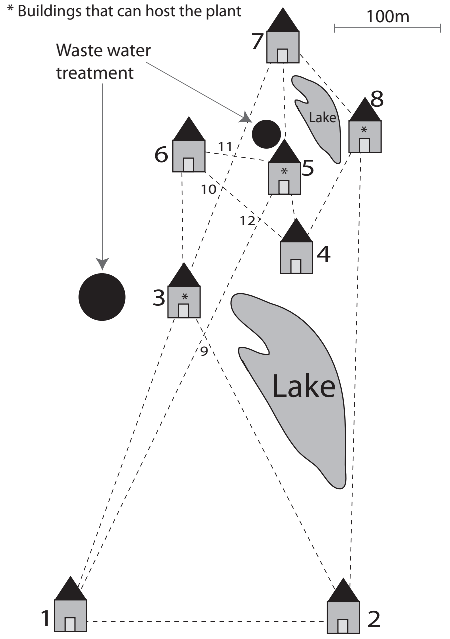
[1] District Energy System Design and OPeration OPtimization problem



	Heating kWth	Hot water kWth	Cooling kWth	Elec-tricity kWel
1	500	35	200	125
2	350	30	350	86
3	470	30	86	150
4	600	55	300	150
5	580	55	300	125
6	500	40	100	110
7	300	35	150	86
8	340	30	75	80
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0

Figure 5.1: District analysed, with the maximum requirements in kW for each energy service and the buildings that can host the plant with the district energy conversion technologies

List of available energy sources[2]

Regarding the energy sources, two types of renewable energy sources can be used, namely two lakes and two wastewater treatment facilities that can provide energy to heat pumps. Regarding the non renewable sources, natural gas is the only one that is considered, since heating oil has been left out except for individual back-up boilers. Other sources such as waste incineration or biomass have been assumed not to be available for this case.

Energy consumption profiles with power and temperature levels

The energy consumption profiles have been developed for this purpose, inspired by the works by Girardin [47] related to a real case district in Geneva (which will be the topic of the next chapter). Six representative periods have been defined with their relative duration in hours/year, and average atmospheric temperature. These periods are shown in Table 5.1. As already mentioned, since the purpose of the method is the *design* of a district energy system, and not the *controlling* of this system, it has been considered sufficient to divide the whole year into 6 periods only, and to make a compromise between degree of detail and resolution time. This simplification has the disadvantage to exclude days with extreme weather events and could therefore favour undersized equipment. Increasing the number of representative periods however would lead to an increased number of variables and

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[2] Remember that these energy sources are used for the *district* energy conversion technologies implemented at the central plant.

Period	Duration		T^{atm}	
summer day	1095	hr/year	25	°C
summer night	1095	hr/year	15	°C
mid-season day	2190	hr/year	14	°C
mid-season night	2190	hr/year	10	°C
winter day	1095	hr/year	1	°C
winter night	1095	hr/year	-5	°C

Table 5.1: Periods considered in the test case with their duration and average atmospheric temperature

therefore of the computation time required to solve the slave optimization problem. This would add one day in the list and require an increased investment in the backup units required to satisfy the extreme conditions. A good compromise to analyse the influence of extreme days, can be achieved by making a more detailed simulation for the interesting solutions resulting from the optimization without the extreme periods, including the extreme days and/or storage devices, according to what has been done in [99].

The consumption profiles are given in Figures 5.3- 5.5. The temperature levels for the heating requirements, corresponding to the supply temperature T_S and the return temperature T_R of the hydronic circuit in the building, have been set to $T_S = 35$°C and $T_R = 32$°C for the mid-season periods and $T_S = 58$°C and $T_R = 48$°C for the winter periods, according to Figure 5.2, based on [83, 47]. The water used for the hot water requirements has been assumed to enter the buildings at 10°C and to have to be heated up to 60°C. Finally for the cooling requirements the temperatures have been set for all the buildings to $T_S = 18$°C and to $T_R = 21$°C. These latter values, which are higher than what is usually admitted ($T_S = 6$°C and to $T_R = 12$°C) have been estimated based on what could be found for modern installations [106].

Comparing the list of available energy sources together with the energy service requirements of the district including the temperature and power levels of these requirements, the following technologies are considered as reasonable and taken up in the list of possible district energy conversion technologies:

1. Heating and hot water:
    - A heat pump, connecting the return pipe of the cooling network on the evaporator side with the supply pipe of the heating network on the condenser side. This heat pump thus allows the energy transfer between the buildings requiring cooling and the buildings requiring heating. This heat pump will be abbreviated HP1 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.
    - A second heat pump, connected to the lake(s) and having therefore its

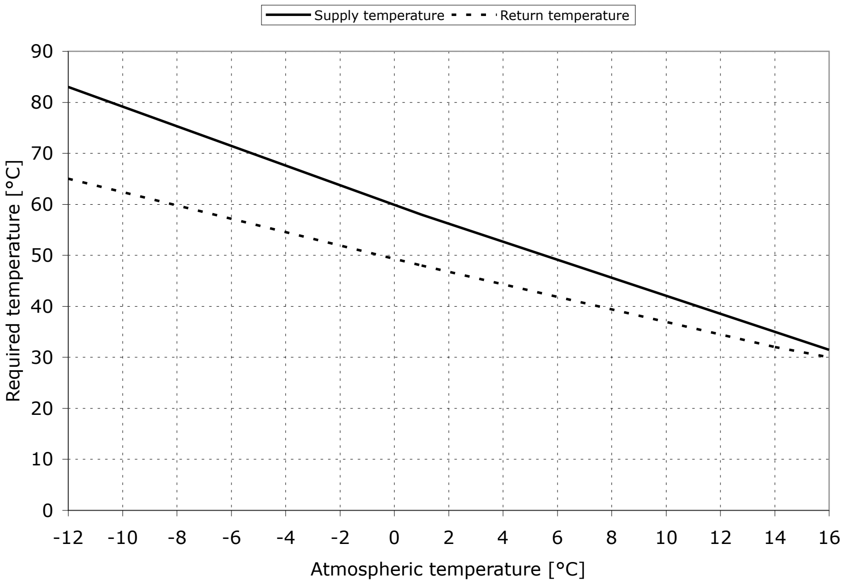

Figure 5.2: Heating supply and return temperatures of the hydronic circuit of the buildings, assuming radiators [47]

evaporator temperature determined by the temperature of the lake. A maximum temperature difference of 4°C is assumed in the evaporator for the water coming from the lake, in order to avoid freezing in winter (the temperature of the water in the lake being 6°C). This heat pump will be abbreviated HP2 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.

- A third heat pump, converting energy recycled from the wastewater treatment facility(ies) and having therefore its evaporator temperature determined by the temperature of the wastewater treatment facility(ies). As mentioned in Section 4.6, a temperature difference of 10°C is assumed in the evaporator for the water coming from the wastewater treatment facility. This heat pump will be abbreviated HP3 in the following, its lower bound is 1 000 kWth and its upper bound 5 000 kWth.

2. Cooling:

   - The HP1 heat pump mentioned above, allowing the heat transfer between buildings.
   - ”Free” cooling using water from the lake(s) that is being circulated through the district.

3. Electricity:

   - A gas engine (abbreviated GE), used in cogeneration mode, with a lower bound at 1 000 kWel and an upper bound at 5 000 kWel.

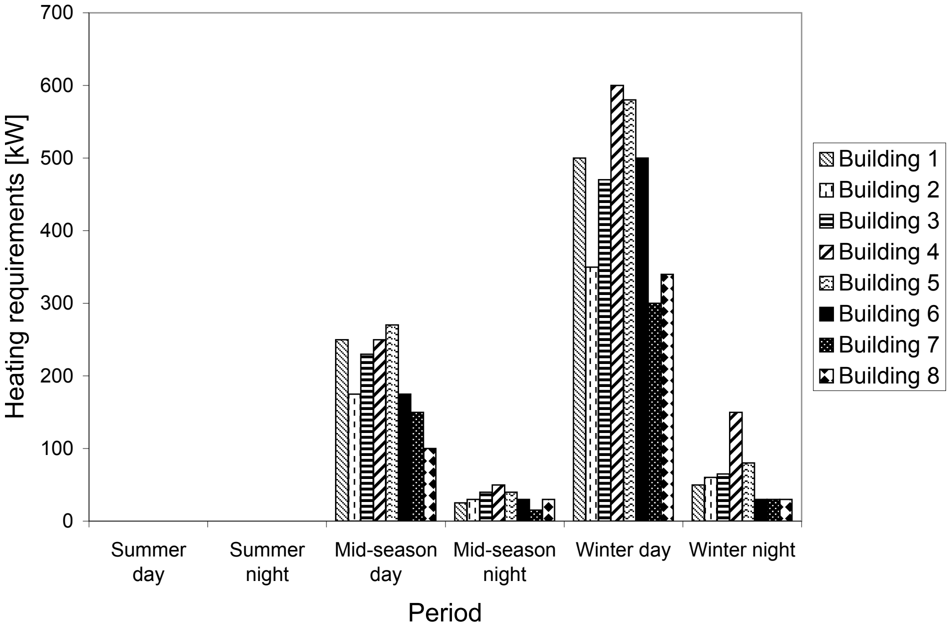

Figure 5.3: Heating requirements profile for the test district

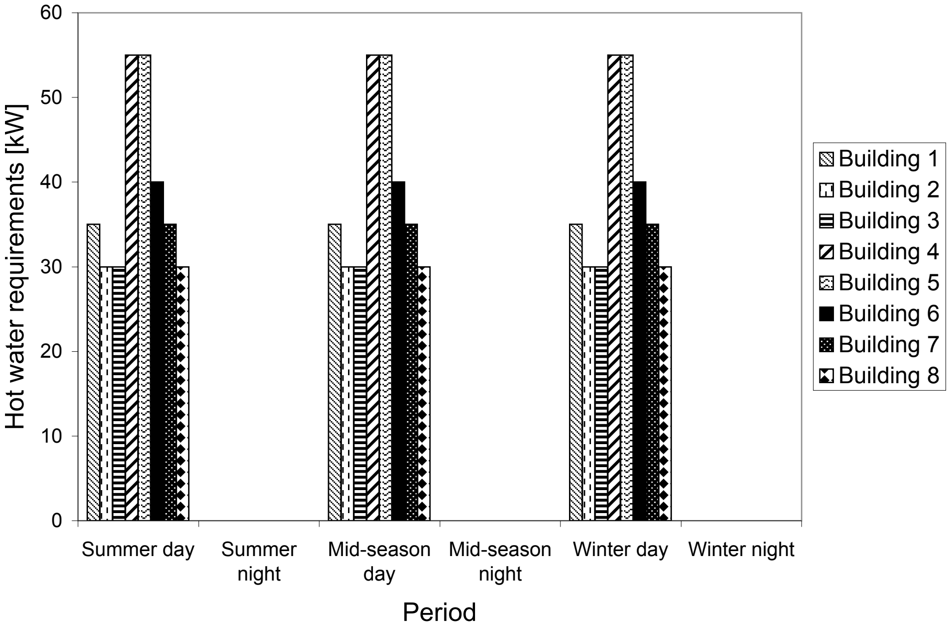

Figure 5.4: Hot water requirements profile for the test district

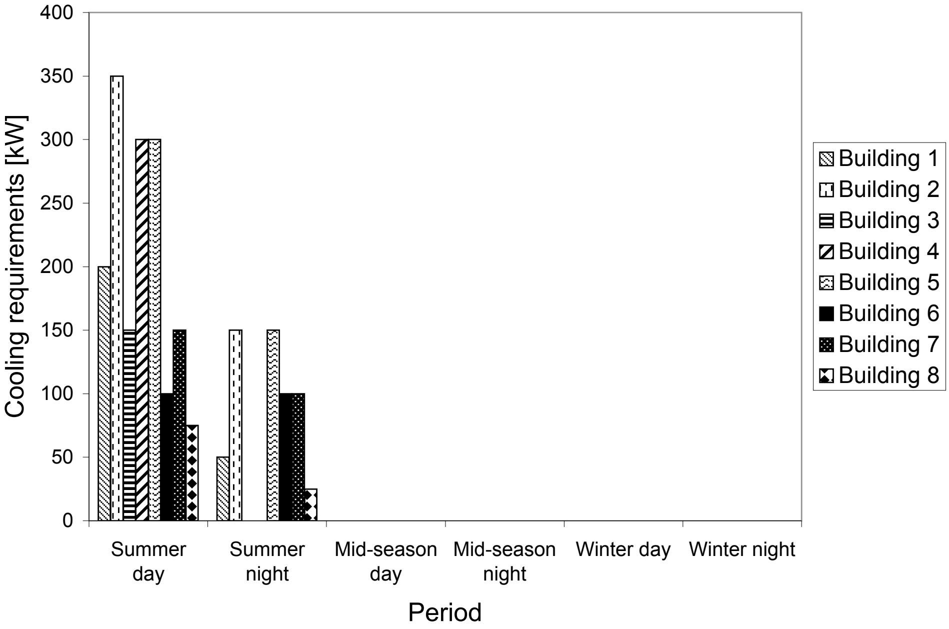

Figure 5.5: Cooling requirements profile for the test district (Considering the atmospheric temperature of 15°C given in Table 5.1 for the summer night period, the fact that they are some cooling requirements during this period may seem inconsistent. The supply and return temperatures of the cooling circuit in the building amount indeed to 18°C, respectively, 21°C. However, cooling requirements can occur even when the atmospheric temperature is below the temperature level of the circuit in the building, particularly for the air-conditioning of computer rooms. An additional constraint in the data processing routine could nonetheless force the method to use air cooling in such cases.)

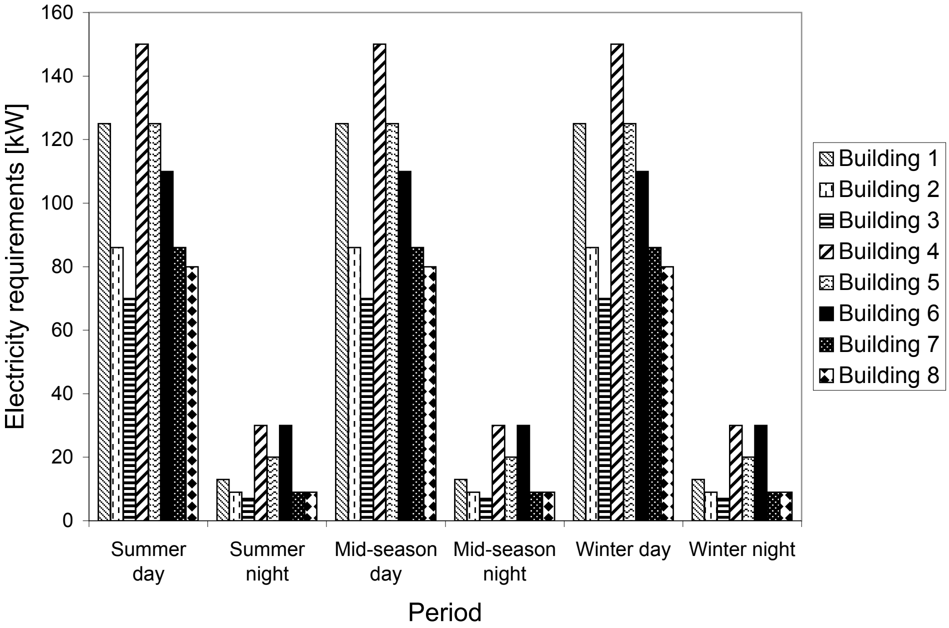

Figure 5.6: Electricity requirements profile for the test district

Parameter	Summer	Mid-season	Winter
Temperature of the lakes °C	8	6	6
Temperature of the municipal wastewater treatment facility in summer °C [10]	22	18.5	16

Table 5.2: Temperature level of the lake and the wastewater treatment facility

Parameter	Range	Value	Unit	Reference
C_{fix}^{pipe}	0-300 mm ø	753	CHF	[77]
c_{prop}^{pipe}	0-300 mm ø	7	CHF/m	[77]
C_{fix}^{boiler}	100-650 kWth	1000	CHF	[48]
c_{prop}^{boiler}	100-650 kWth	218	CHF/kWth	[48]
C_{fix}^{aw}	100-650 kWth	1000	CHF	[104]
c_{prop}^{aw}	100-650 kWth	1890	CHF/kWth	[104]
C_{fix}^{ww}	350-650 kWth	42833	CHF	[28]
c_{prop}^{ww}	350-650 kWth	126	CHF/kWth	[28]
C_{fix}^{chiller}	0-350	2500	CHF	Eval. after [28]
$c_{prop}^{\text{chiller}}$	0-350 kWth	2835	CHF/kWth	Eval. after [28]
r^i	$i = aw, boiler, chiller, hex, pipes, pump, ww$	0.08		[37]
F_m^i	$i = aw, boiler, chiller, hex, pipes, pump, ww$	0.06		[37]
M_S^i	year 2006 ($i = aw, boiler, chiller, ww$)	1306.6		[37]
M_S^i	year 1998 ($i = hex, pipes, pump$)	1306.6		[37]

Table 5.3: Parameters for the costing functions in the test case

For the lake(s) and the wastewater treatment facility(ies), it is assumed that enough water resource is available for the heat pumps. In a more detailed analysis (for instance if HP2 or HP3 type heat pumps appear to be promising technologies), the temperature difference of 4°C, respectively 10°C, assumed in the evaporator, should also be optimized. In this case however, the mass flow rate between the lake or the wastewater treatment facility(ies) and the heat pump, should also be considered (this has been neglected in the present thesis). Besides, a limited amount of water could easily be taken into account by setting a constraint on the energy source. The temperature levels for the lake and the wastewater treatment facility are given in Table 5.2

SPATIAL CONSTRAINTS AS WELL AS NODES AND POSSIBLE CONNECTIONS

Spatial constraints are set regarding the possible location of the plant (district energy conversion technologies): buildings 3, 5 and/or 8 (see Figure 5.1). Besides the possible connections, obtained from a routing algorithm, are given (dotted lines on the figure). Other than this, no size related constraints are given in the first

Parameter	Value	Units	Reference
Exergetic efficiency of the individual back-up air/water heat pumps	0.34	[-]	[47]
Exergetic efficiency of the individual back-up water/water heat pumps	0.4	[-]	[47]
Exergetic efficiency of the individual back-up chillers	0.19	[-]	after [27]

Table 5.4: Efficiency parameters related to the individual back-up technologies, used in the test case

optimization run. (A size related constraint could be for instance a limitation on the size of the pipe diameter between two nodes). The effect of spatial constraints will be shown in Paragraph 5.4.2.

Individual back-up technologies
As back-up energy conversion technologies, the following technologies are considered: air/water and water/water heat pumps as well as boilers for heating and hot water, and electric chillers for cooling (see Section 2.2 are considered)[3]. For the heat pumps, the condenser temperature has been considered the same for both heating and hot water (this assumption is penalising for the heat pumps and should be reconsidered in a more refined optimization). To compute the annual investment costs, the parameters given in Table 5.3 have been used. Besides, the efficiencies given in Table 5.4 have been used.

5.3 Optimization

5.3.1 Decision variables

For the district analysed in this chapter, and following the list of selected district energy conversion technologies that are reasonable for this case, the master optimizer optimizes the following 17 decision variables:

1. Supply and return temperatures of the heating network in summer, and winter/mid-seasons: variables 1 to 4
2. Supply and return temperatures of the cooling network in summer (no cooling is assumed during the winter and the mid-seasons): variables 5 and 6
3. Investment or not in a HP1, HP2 and HP3 as well as gas engine GE: variables 7 to 10
4. Design size of heat pumps HP1, HP2 and HP3 as well as gas engine GE: variable 11 to 14
5. Condenser temperature of heat pumps HP1, HP2 and HP3: variable 15 to 17

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[3] For electricity, the back-up is the grid.

Beside these decision variables, remember that the master optimization also defines the CO_2 weighting factor. This factor is a mathematical tool to take into account CO_2 emissions in the single objective slave optimization. Therefore, it is a purely *mathematical* decision variable, and differs in that sense from the other decision variables which are *engineering* decision variables. Besides, note that the condenser temperatures of the heat pumps do not necessarily equal the supply temperature of the heating network, as the three heat pumps and the gas engine can be put in series. In fact, in an optimally integrated system these energy conversion technologies *will* be in series, in order for the heat pumps to operate at better COPs.

All parameters used for the test case are given in Tables 5.3 to 5.5 (regarding the parameters of the district energy conversion technologies, please refer to the model descriptions, Section 4.3).

Parameter	Value	Units	Reference
CO_2 emissions of electricity from the grid $co_2{}^{\mathrm{grid}}$ (European mix)	0.450	[kg/kWh]	[40]
CO_2 emissions for natural gas $co_2{}^{\mathrm{gas}}$ (including transportation)	0.230	[kg/kWh]	[40]
CO_2 emissions for heating oil $co_2{}^{\mathrm{oil}}$ (including transportation)	0.293	[kg/kWh]	[40]
Cost for electricity from the grid c^{grid}	0.13	[CHF/kWh]	[15]
Cost for natural gas c^{gas}	0.04	[CHF/kWh]	[15]
Cost for heating oil c^{oil}	0.0645	[CHF/kWh]	[15]
Efficiency of the circulation pumps	80%	[-]	
Friction coefficient in the pipes λ	0.02	[-]	[77]
Grid efficiency ϵ^{grid}	90%	[-]	
Heat transfer coefficient in the pipes K	0.203	[W/mK]	[77]
Isobaric specific heat of water $cp_{H_2O}^{\mathrm{liq}}$	4.178	[kJ/(kg K)]	
Overall heat transfer coefficient in heat exchangers	800	[W/(m2 K)]	[26]
Minimum ΔT in the heat-exchangers between the district networks and the hydronic circuit of the buildings	2	[°C]	
Selling price of electricity b^{grid}	0.09	[CHF/kWh]	[15]

Table 5.5: Values of the thermodynamic and distributed energy related parameters, used in the optimization phase in general

5.3.2 Conditions defined for the optimization

To perform the optimization, it was decided that the excess electricity generated by the gas engine could be sold at a price of 0.09 CHF/kWhel [15]. Besides, in the accounting of the CO_2 emissions, the avoided CO_2 when selling electricity to the grid, has not been accounted for. In other words, to compute the CO_2 emissions, when electricity is sold to the grid, the total CO_2 emitted by the gas engine to generate this electricity has been taken into account, without deducing the CO_2 emissions that the grid would have emitted to generate this same amount of electricity, and that are "saved" by the cogeneration gas engine.

The tolerance set for the Cplex solver amounts to 5%, meaning that the slave optimization stops when it has found a solution within 5% of the evaluated optimal value.

5.3.3 Solution phase analysis

The slave optimizer optimizes the variables listed in Paragraph 3.4.4. According to the values chosen by the master optimizer and the subsequent data processing performed by the data processor, the number of variables optimized by the slave optimizer ranges between 35 000 and 50 000 continuous variables and 250 and 850 binary (0-1) variables. The large number of variables optimized by the slave optimizer is due to the number of indices for each type of variable. Let us analyse for instance the variable characterizing the energy flows between nodes in the network. For the slave optimizer, there are as many variables as there are possible combinations of connections (between two nodes), periods, temperature intervals[4] and sub-networks[5]:

Number of possible connections in the test district:	21
Number of periods:	6
Number of temperature intervals:	∼20
Number of sub-networks:	4

In other words, there are $21 \cdot 6 \cdot 20 \cdot 4 = 10\,080$ decision variables only for the energy flows. The same number of decision variables are related to the mass flows. Further important decision variables include the energy conversion technologies, and the variables related to the total emissions and costs.

To make the optimization of the test case, 17 000 iterations of the master optimizer have been performed. Solving this problem took 4 days 8 hours and 29

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[4] The exact number of temperature intervals describing the whole system (the highest temperature being for instance the temperature of the heat from the gas engine and the lowest temperature the supply temperature of the cooling network) depends strongly on the set of variables defined by the master optimizer.

[5] Supply and return networks for both heating and cooling.

minutes of computation time on 4 Intel Pentium4 2'800 MHz computers (the resolution has been parallelized on 4 computers [76]). The optimization time indicated here is of course strongly dependent on the number of iterations done by the master optimization[6] but also on the tolerance that the Cplex solver used in the present thesis allows to define.

5.3.4 Pareto optimal frontier

The results of the optimization are shown on the Pareto curve of Figure 5.7. The most interesting configurations are summarized in Table 5.6. In this table, the indices a and b for the heat pump HP3 correspond to the two heat pumps that are implemented in series at the wastewater treatment facility, due to the high temperature difference occurring at the evaporator side[7]. From the Pareto optimal frontier, three distinct groups of configuration types (hereafter clusters) can be recognised:

Cluster 1 "HP3+GE+Lake" : The HP3 heat pump is implemented together with the gas engine , providing heating, hot water and electricity to all the buildings. The cooling is provided by the water from the lake to all the buildings.

Cluster 2 "HP2+GE+Lake" : The HP2 heat pump is implemented together with the gas engine , providing heating, hot water and electricity to all the buildings. The cooling is provided by the water from the lake to all the buildings.

Cluster 3 "GE+Lake" : Only the gas engine is implemented to provide heating, hot water and electricity to some or all of the buildings. The cooling is provided by the water from the lake to all the buildings. No district heat pumps are implemented in this cluster.

Before going into details in the analysis of the different clusters, a few general statements shall be made.

The reference configuration, called "Initial", getting the electricity from the grid, heating and hot water from a boiler, and cooling from an electric chiller, does not appear on Figure 5.7. Actually, such a configuration would emit 5 779 tons-CO_2/year and cost 1.98 mio-CHF/year, thus overshooting the axis of the figure in terms of costs, and performing poorly in terms of CO_2 emissions.

The optimal configuration in terms of CO_2 emissions (configuration 1A1 on Figure 5.7 and Table 5.6) emits 3 407 tons-CO_2/year (59% of the "Initial" configuration)

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[6] The number of iterations is estimated empirically. The iterations are stopped when no improvement can be obtained from further iterations.

[7] Remember that when the temperature decrease of the heat source on the evaporator side exceeds 4°C, two smaller heat pumps are implemented in series instead of one large heat pump.

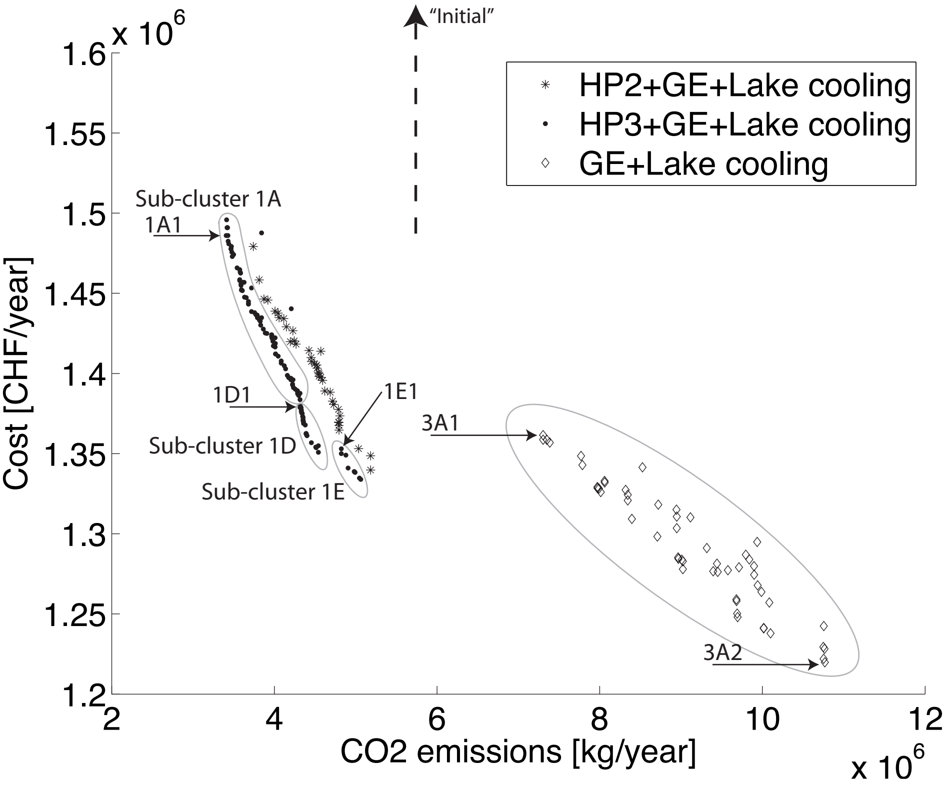

Figure 5.7: Pareto optimal frontier

Configuration	1A1	1A2	1B1	1D1	1E1	3A1	3A2
Annual CO_2 emissions ton-CO_2/year	3 407	4 256	3 582	4 350	4 824	7 303	10 769
Costs mio-CHF/year	1.49	1.39	1.46	1.37	1.35	1.36	1.22
Percentage Investment	53	46	53	46	44	27	22
Operational	47	54	47	54	56	73	78
Income I^{el}mio-CHF/year	0	0.18	0	0.22	0.26	0.44	1.2
Grid mio-CHF/year	0.28	0.26	0.14	0.26	0.13	0.02	0.02
Gas mio-CHF/year	0.42	0.58	0.54	0.6	0.76	1.26	1.86
HP3a Size MWth	1029	639	1040	634	634	0	0
Inv. CHF/year	174 816	123 469	176 134	122 901	122 901	0	0
T_{cond} °C	75	80	79	80	77	-	-
COP summer	3.06	3.03	3.05	3.03	3.04	-	-
COP mid-season	2.91	2.89	2.90	2.89	2.90	-	-
COP winter	2.82	2.79	2.80	2.79	2.81	-	-
HP3b Size MWth	1029	639	1040	634	634	0	0
Inv. CHF/year	174 816	123 469	176 134	122 901	122 901	0	0
T_{cond} °C	80	85	84	85	82	-	-
COP summer	3.10	3.08	3.09	3.08	3.09	-	-
COP mid-season	2.95	2.93	2.94	2.93	2.94	-	-
COP winter	2.86	2.83	2.84	2.83	2.84	-	-
GE Size MWel	1753	2532	1731	2540	2540	1978	3857
Inv. CHF/year	190 444	239 621	188 987	240 101	240 101	205 363	311 681
ϵ_{el} %	42.88	43.47	42.86	43.47	43.47	43.08	44.14
ϵ_{th} %	47.12	46.53	47.14	46.53	46.53	46.92	45.86
Lake cooling kWth	1 625	1 625	1 625	1 625	1 625	1 625	1 625
Network Inv. CHF/year	192 121	187 630	199 014	189 293	190 908	176 933	186 590
Pumps Inv. CHF/year	5 624	5 493	5 813	5 542	5 661	4 324	5 683
$T_{\mathrm{hs},t}$ °C Summer	70.4	71.9	68.5	72.4	110.6	103.2	94.7
Mid-season and winter	77.0	77.6	75.9	77.6	77.5	98.0	103.0
$T_{\mathrm{hr},t}$ °C Summer	36.4	49.0	49.4	53.2	53.2	58.1	88.9
Mid-season and winter	52.6	50.1	51.8	51.5	51.5	51.7	53.5
$T_{\mathrm{hs},t} - T_{\mathrm{hr},t}$ °C Summer	34.0	22.9	19.1	19.2	57.4	45.1	5.8
Mid-season and winter	24.4	27.5	24.1	26.1	26.0	46.3	49.5
$T_{\mathrm{cs},t}$ °C $\forall t$	10.2	10.0	11.0	10.0	10.0	10.5	10.2
$T_{\mathrm{cr},t}$ °C $\forall t$	18.9	18.9	19.0	18.8	18.8	17.0	18.9

Table 5.6: Main configurations for the test case, with the values given in Tables 5.3 and 5.5. As a comparison, configuration "Initial", not shown in the table, implementing boilers and electric chillers and taking electricity from the grid, emits 5 779 tons-CO_2/year and costs 1.98 mio-CHF/year. (The annual costs are given after deduction of the income resulting from the electricity sales. Therefore, to compute the percentage of investment and operational costs, this income is added up again to the total costs.)

and costs 1.49 mio-CHF/year (75% of the "Initial" configuration). This configuration features a HP3 type district heat pump, together with a gas engine, a cooling network with water from the lake, and takes the electricity partly from the grid (summer periods as well as all the night periods) and partly from the gas engine (mid-season and winter day periods). All buildings are connected to the networks, be it for cooling or for heating and hot water. The networks are shown in Figure 5.8.

The optimal solution in terms of annual costs (configuration 3A2 on Figure 5.7 and Table 5.6) emits 10 769 tons-CO_2/year and costs 1.22 mio-CHF/year. This solution features a gas engine that delivers heating and hot water to all eight buildings, with lake cooling for all buildings, and electricity from the grid during the summer night period (in all other periods, the gas engine generates enough electricity for the district and even sells some to the grid). The heating and cooling networks are shown in Figure 5.9. Due to the way of accounting for the CO_2 emissions, this configuration emits more than the "Initial" configuration (186%). See Paragraph 5.3.7 for further explanations regarding this issue.

Figures 5.10 and 5.11 show for each period the composite curves for the district heating system for these two configurations (note that the scale for the X-axis changes according to the period). On the plots, the hot composite curve represents the heat provided by the district energy conversion technologies, and the cold composite curve the heat required by the district. Note that the periods during which the gas engine is not operated can be easily recognised on these figures, since no high temperature heat (up to 570°C) is generated (for instance during period 1, the summer day period, of configuration 1A1). The least CO_2 emitting configuration features also the better energetic integration. For configuration 1A1, the entire heat is provided by the heat pump during periods 1 (summer day period) and 4 (mid-season night period). Due to the constraint that the heat pump cannot be operated less than 20% of the time (to avoid shutting the heat pump on and off for a few minutes only), the heat pump generates more heat than required during these two periods. In a more refined optimization, this constraint should be modified, especially for a case like this one, in which the heat pump, HP3, actually consists of two smaller units in series (HP3a and HP3b).

It is noteworthy that in clusters 1 and 2, *all* buildings are connected to both the heating and the cooling networks. In cluster 3, even if the heating network does not always connect all buildings (see Paragraph 5.3.7), the cooling network does provide cooling to all buildings. Therefore, since water from the lake provides cooling to the whole district in summer (whatever the cluster), one may wonder why a separate heating network provides the heat, and not individual water/water heat pumps that could use the cooling network as heat source. This point will be taken up in more details in Paragraph 5.4.1. Regarding the cooling network supply and return temperatures, one can see from Table 5.6 that they almost always correspond to the minimum, respectively maximum, allowed temperatures. For the supply temperature, 10°C indeed corresponds to the temperature of the lake (8°C) plus the minimum temperature difference of 2°C, and for the return temperature, 19°C correspond to the return temperature of the hydronic circuits in the buildings (21°C) minus the minimum temperature difference of 2°C. This fact is not surprising, since the heat "gains" (the opposite of the heat losses for heating networks) have been neglected and therefore advantage is taken of the maximum possible temperature difference between the supply and return pipes, in order to minimize the water that needs to be pumped. Finally, for all configurations, an interaction between the district and the grid is always present, be it to buy or to sell electricity.

To be Pareto optimal, the configurations implementing district heat pumps need to have a HP3. The configurations of cluster 2, "HP2+GE+Lake", are never Pareto optimal. This is a consequence of the low temperature heat source being at a higher temperature level for HP3 (wastewater treatment facility) than for HP2 (lake), resulting in a better COP for HP3 compared to HP2. It might appear surprising that the difference of the results between clusters 1 and 2 is not larger. The main explanation for this lies in the fact that the COP difference for both types of heat pumps can be less than 5% (which is already a small difference), and on top of this the tolerance of 5% set for the slave opimization can introduce a bias that can partly offset the advantage of HP3 relative to HP2 (see Appendix A.3 for further explanations).

The district heat pump HP1 is never used. This is due to the tight constraints set on this technology. *District* cooling can indeed be provided either by this heat pump or by circulating water from the lake. For both options, pipes and a circulating pump need to be implemented, so that no difference exists between the two options at this level. However, HP1 generates an investment in the technology, which water from the lake doesn't require[8]. Besides, HP1 can only be used if in parallel to the cooling requirements, heating or hot water requirements are to be satisfied. In the case analysed here, this occurs only during the summer day period, for which cooling requirements and hot water requirements are to be satisfied simultaneously. Therefore, if HP1 was implemented during the summer day period, another cooling technique should be sought for during the summer night period, making the overall resulting system for both periods less profitable than having only one cooling system.

Clusters 1 to 3 shall now be explained in more details.

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[8] The costs for the heat exchanger between the lake and the network have been neglected.

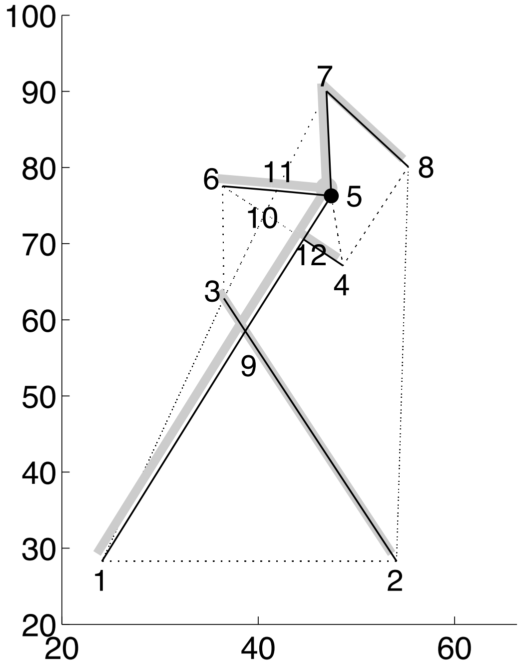


Figure 5.8: Cooling network (thin black line), heating and hot water network (large grey line) for configuration 1A1 (see Figure 5.7 and Table 5.6). The energy plant is located on node 5.

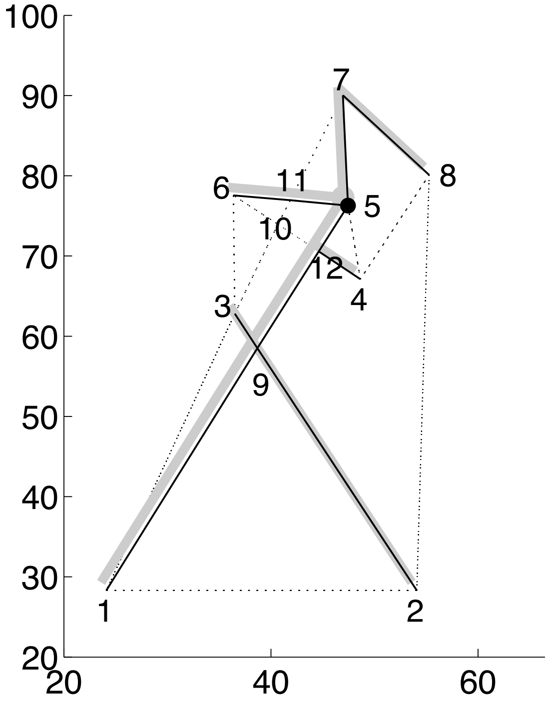
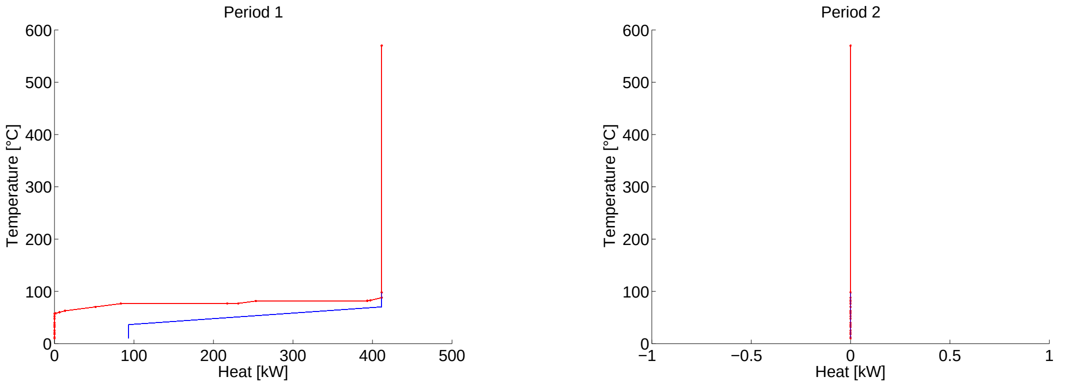
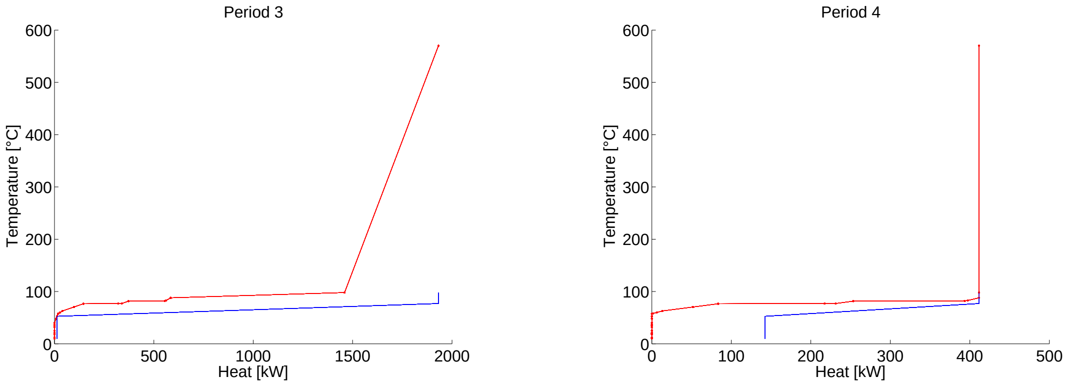


Figure 5.9: Cooling network (thin black line), heating and hot water network (large grey line), for configuration 3A2 (see Figure 5.7 and Table 5.6). The energy plant is located on node 5.



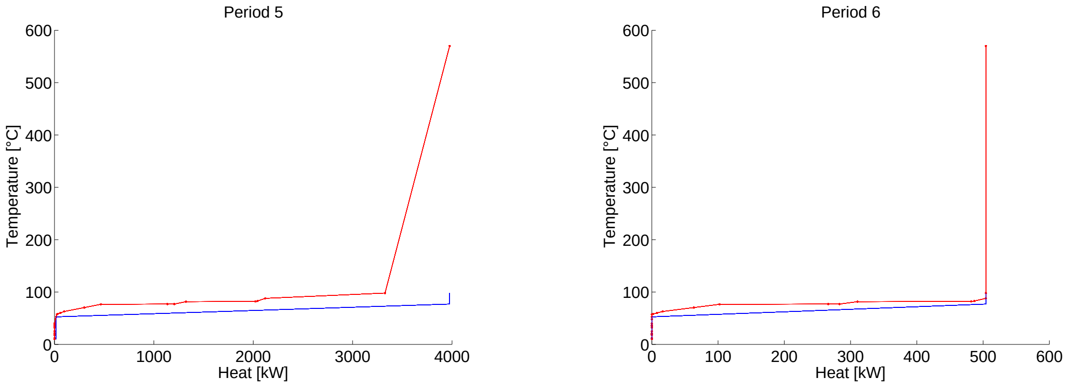
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

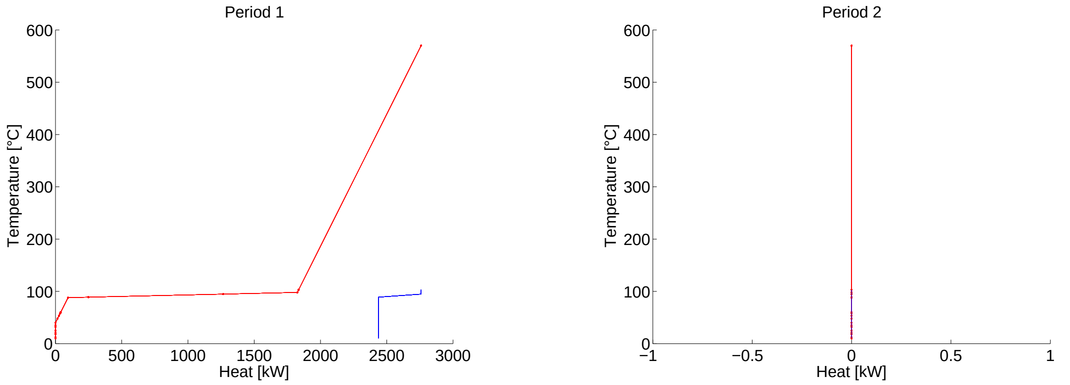
Composite curve of the mid-season night period



Composite curve of the winter day period

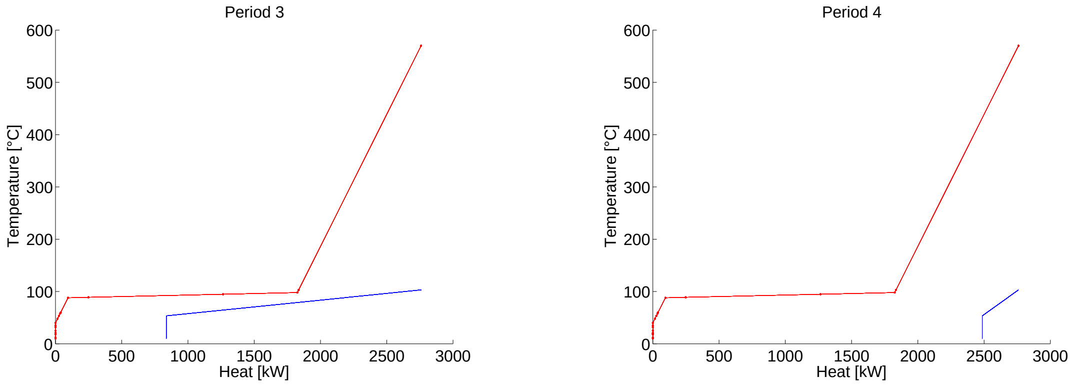
Composite curve of the winter night period

Figure 5.10: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration 1A1 (see Figure 5.7 and Table 5.6)



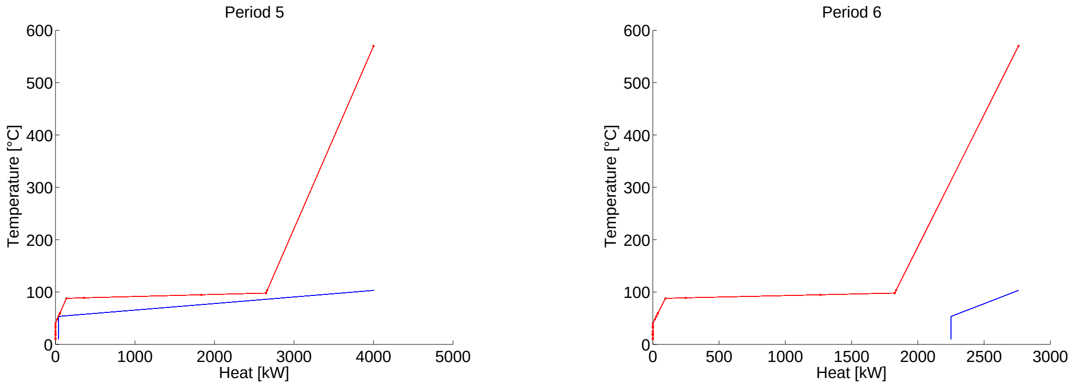
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

Composite curve of the mid-season night period



Composite curve of the winter day period

Composite curve of the winter night period

Figure 5.11: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration 3A2 (see Figure 5.7 and Table 5.6)

5.3.5 Cluster 1 ”HP3+GE+Lake”

Cluster 1 implements an HP3 type heat pump combined with a gas engine, and cooling from the lake. This cluster contains the majority of the Pareto optimal configurations. Looking at Figures 5.12 and 5.13, showing the correlation between the sizes of the GE or the HP3, and the CO_2 emissions, two interesting features appear:

1. As the size of the heat pump decreases, the size of the gas engine increases and the emissions increase (but the cost decrease).
2. Cluster 1 can be decomposed into four different sub-clusters (1A to 1E, note that cluster 1C doesn't exist...) that are very distinct on these two figures.

The fact that the size of the gas engine increases while the size of the heat pump decreases is not surprising and will not be further discussed.

The different sub-clusters of cluster 1, on the other hand, call for a comment. What distinguishes the different sub-clusters of cluster 1 are the weighting factor set for the CO_2 emissions in the slave optimization, on one hand, and the operating strategy of the gas engine, on the other. In sub-cluster 1A, the weighting factor has been set very high (between 2 to 5 times higher than in the other sub-clusters), thus furthering solutions with low CO_2 emissions. It is therefore of no surprise that the configuration featuring the least emissions (configuration 1A1) belongs to cluster 1A. For the same sizes of gas engines, the configurations belonging to sub-cluster 1A indeed emit less CO_2 than the configurations belonging to the other sub-clusters. See for instance 1A2, 1D1 and 1E1 on Figure 5.13, for which all the values for the other decision variables (Table 5.6) are pretty much the same (except for the summer supply temperature as explained hereafter). Sub-clusters 1D and 1E, on the other side, differ in the operating strategy of the gas engine. In sub-cluster 1D, the gas engine is not operated during the summer day period (which is clearly recognisable in Figure 5.14 where no high temperature heat, up to 570°C, is available during period 1). The heat required for the hot water purposes is provided by the heat pumps running with electricity from the grid, just as the remaining electricity consumption of the buildings that is satisfied with electricity from the grid. On the other hand, in sub-cluster 1E, the heat for the hot water during the summer day period is provided by the gas engine and no heat pump is operated (this is again visible in Figure 5.15 that shows heat available from 570°C and below). Beside emitting more CO_2, this latter operational strategy results in a supply temperature of the heating network in summer which is influenced only by the temperature level of the heat generated by the gas engine, and not the heat pump. This supply temperature is therefore much higher in sub-cluster 1E, than in sub-cluster 1D (compare for instance the summer supply temperatures of configurations 1D1, 72.4°C, and 1E1, 110.6°C, in Table 5.6). Regarding the costs, 1E1 is cheaper since it needs to buy less electricity from the grid.

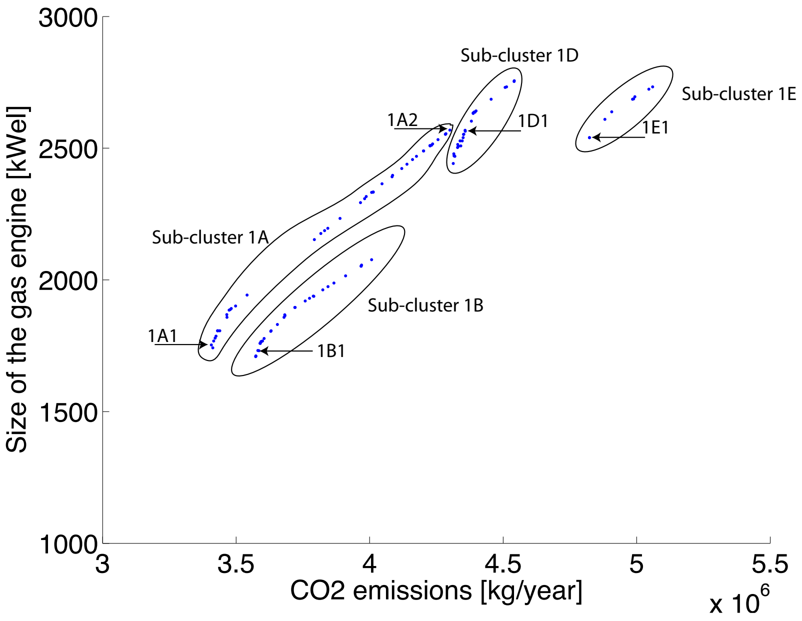


Figure 5.12: Correlation between the size of the gas engine and the annual CO_2 emissions, for cluster 1 “HP3+GE+Lake“, with the parameters of Tables 5.5 and 5.3, and the values of the decision variables given in Table 5.6

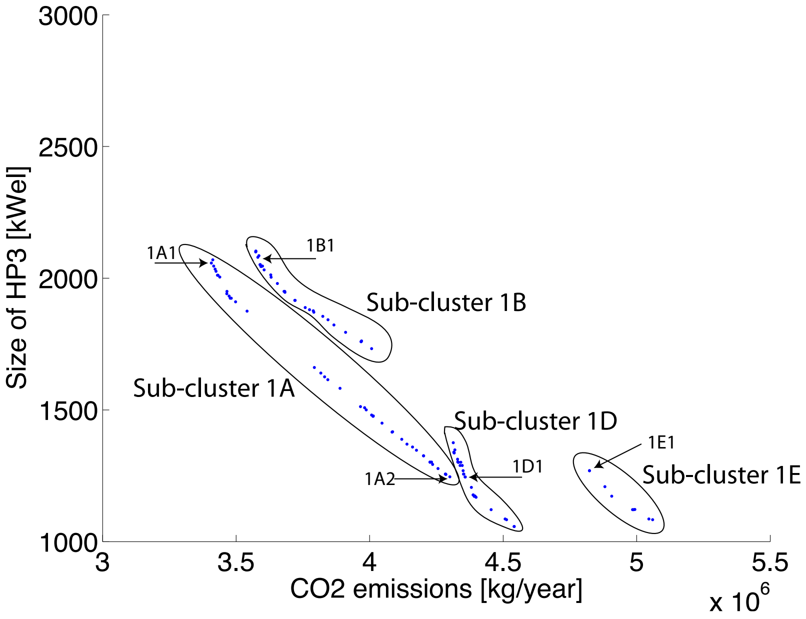
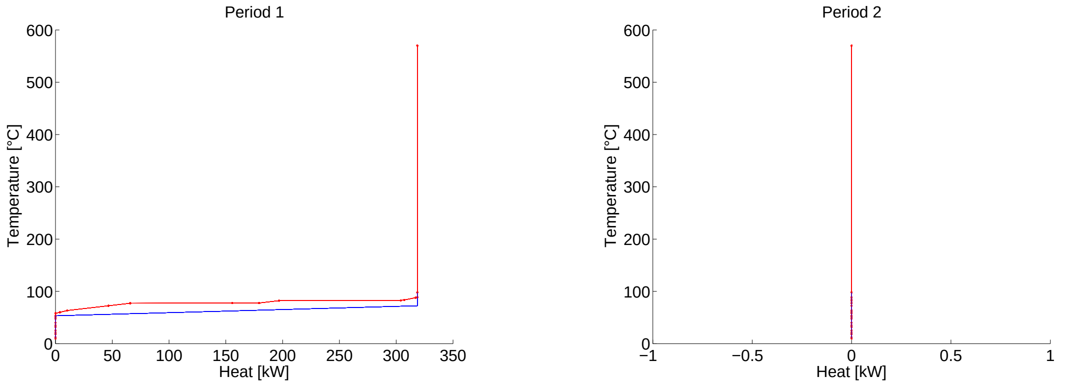
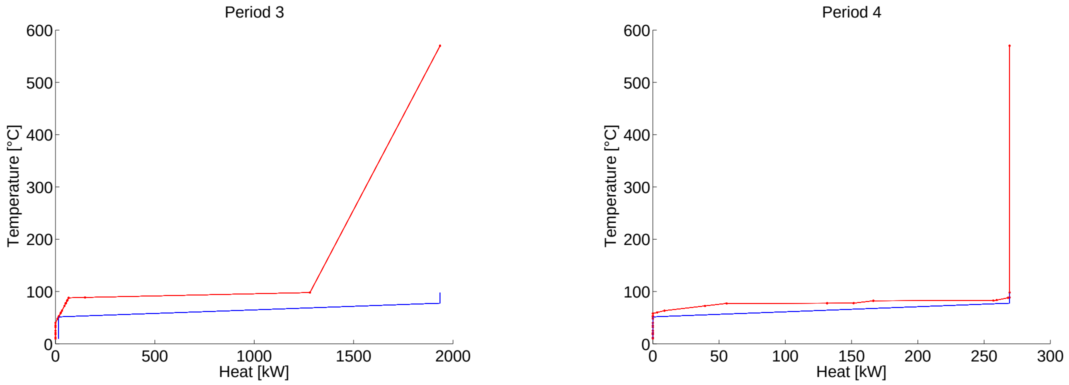


Figure 5.13: Correlation between the size of heat pump HP3 and the annual CO_2 emissions, for cluster 1 “HP3+GE+Lake“, with the parameters of Tables 5.5 and 5.3, and the values of the decision variables given in Table 5.6



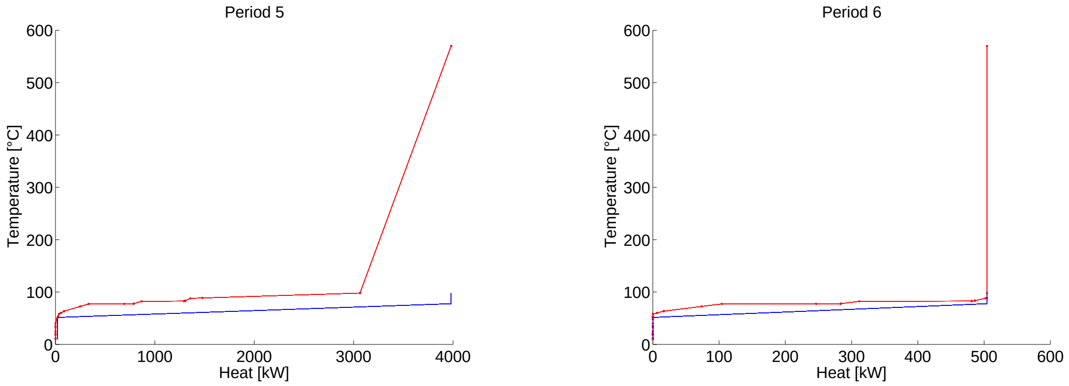
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

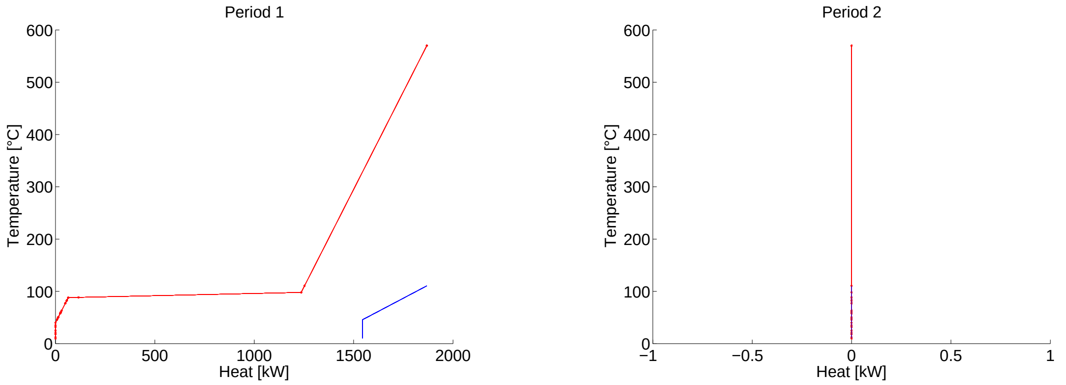
Composite curve of the mid-season night period



Composite curve of the winter day period

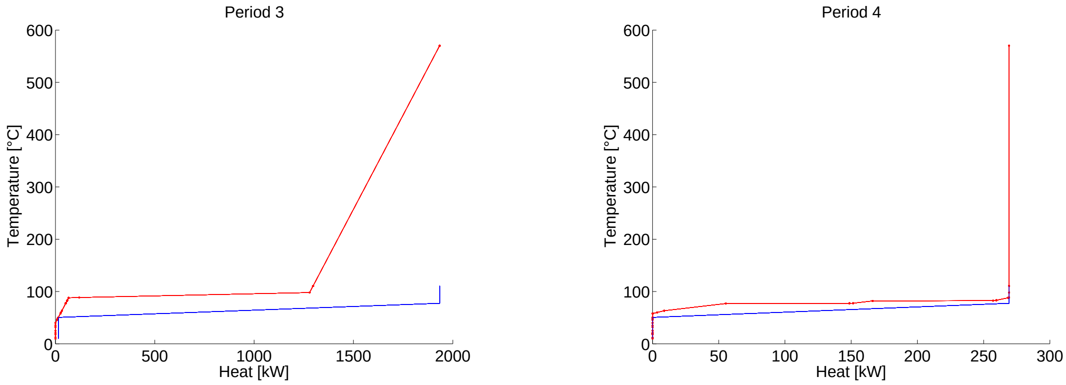
Composite curve of the winter night period

Figure 5.14: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration 1D2 (see Figure 5.7 and Table 5.6)



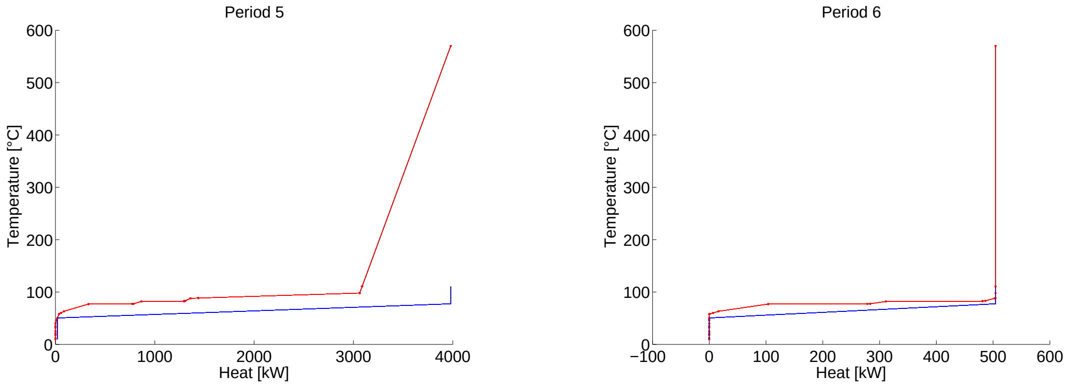
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

Composite curve of the mid-season night period



Composite curve of the winter day period

Composite curve of the winter night period

Figure 5.15: Composite curves for the heating and hot water requirements for configuration 1E1 (see Figure 5.7 and Table 5.6)

5.3.6 Cluster 2 "HP2+GE+Lake"

As can be seen on Figure 5.7, cluster 2 does not contain any Pareto optimal configuration. The reason why the evolutionary optimizer MOO keeps this cluster, is the result of an optimization parameter setting requiring that at least 3 clusters are kept in the final Pareto curve. This allows for the decision makers to see how certain sub-optimal configurations perform compared to the optimal solutions. Since the purpose of the present thesis is the *development* and *validation* of the DESD(OP)^2 method, the further analysis of this cluster is not considered as relevant at this stage.

5.3.7 Cluster 3 "GE+Lake"

In this cluster, the only district energy conversion technology implemented for heating and hot water is the gas engine (cooling is provided by water from the lake). The emissions increase as the size of the gas engine increases, and the cost decreases. Note that increasing the number of iterations would have made this cluster more compact, however without any dramatic improvement regarding the optimal solution in terms of costs (configuration 3A2).

As a matter of fact, all the configurations in this cluster emit more CO_2 than configuration "Initial" described above, that would be the closest to what the majority of the buildings still tend to have nowadays, and that emits 5 779 tons-CO_2/year. However, all the configurations of cluster 3 have a positive electricity balance in the sense that they sell more electricity to the grid, throughout the year, than they buy. Configuration 3A1, for instance, has a positive balance of 4 716 340 kWh/year. As explained in Section 5.3.2, the avoided CO_2 has not been accounted for to compute the results. Figure 5.16 shows how the configurations of Table 5.6 change when the avoided CO_2 is taken into account.

For the configurations featuring a smaller size for the gas engine, like configuration 3A1 that has the smallest gas engine (1 978 kWel), the plant cannot serve all the buildings for heating and hot water, as can be seen of Figure 5.17. Therefore, only the buildings in the vicinity of the plant are connected to the district heating network. The reason why for configuration 3A1 building 3 is connected and not building 6, which would be closer to the plant, is the smaller heat requirements of building 3. The gas engine of configuration 3A1 is too small to meet the heating and hot water requirements of building 6 (in addition to the other buildings connected). The buildings not connected have their own boiler. The fact that the buildings not connected have a back-up boiler and not an air/water heat pump seems in contradiction with the often heard statement in Switzerland nowadays that air/water heat pumps become profitable within about 5 years of installation. However the price considered for the oil in the present thesis is the price paid by the utilities, which is lower than what would be paid by the end-users. Table 5.7 shows the influence of the oil price on the choice of the back-up device. These results have been obtained by running the slave optimization with the parameters of configuration 3A1, except for the oil price (the electricity price being kept constant).

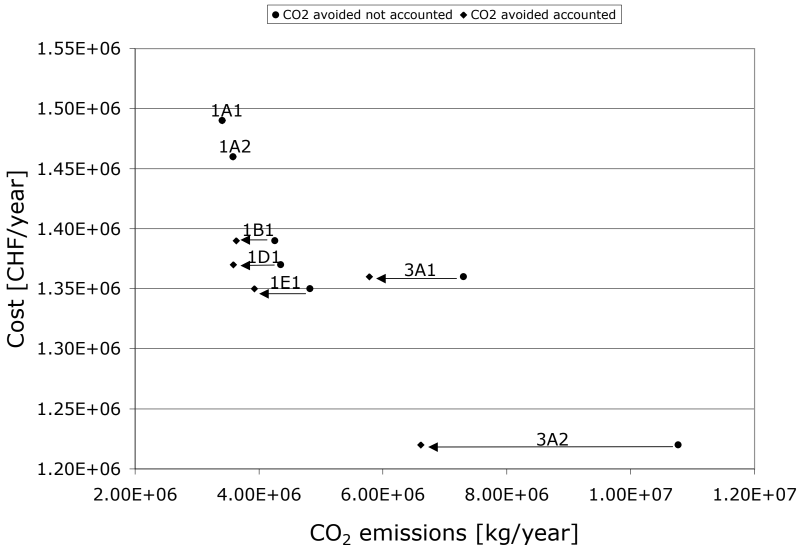


Figure 5.16: Difference in the annual CO_2 emissions for the configurations given in Table 5.6 with and without accounting of the avoided CO_2

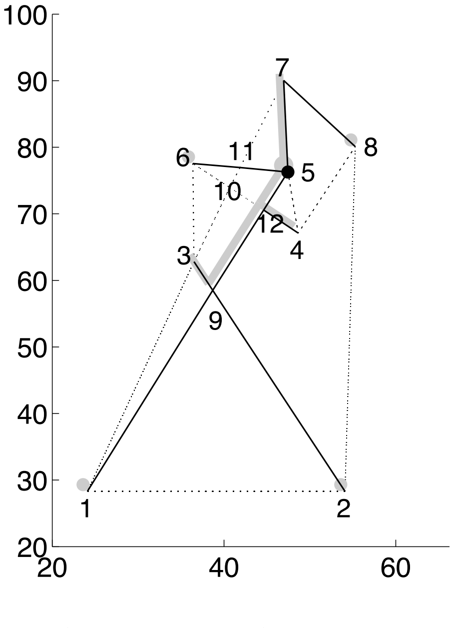


Figure 5.17: Cooling network (thin black line), heating and hot water network (large grey line), and individual back-up boilers (grey circles on nodes 1, 2, 6 and 8), for configuration 3A1 (see Figure 5.7 and Table 5.6)

Oil price CHF/kWh	Buildings implementing a boiler	Buildings implementing an air/water heat pump
0.0645	1, 2, 6 and 8	None
0.08	1, 2, 6 and 8	None
0.09	6 and 8	1 and 2
0.1	None	1, 2, 6 and 8

Table 5.7: Influence of the oil price on the implementation of boilers or air/water heat pumps in configuration 3A1

5.4 Further analysis of the results

Beside the analysis of the clusters themselves, further interesting elements can be gained from the results obtained. These elements are explained in this section.

5.4.1 What about using only one supply pipe and one return pipe?

Considering the fact that *all* Pareto optimal configurations implement cooling with water from the lake for *all* buildings, the question that arises at this stage is: why not using the cooling network (in other words the water from the lake circulating through the pipes) as a heat source, in winter, to implement water/water heat pumps along the network to provide all the heating and hot water requirements. Up to now, the method considered that the heating and the cooling network where two different entities that could be connected only at the plant, by means of a HP1 type heat pump. However, a more novel type of district energy system would be to have only one supply and one return pipe, and to use the circulating water as a low temperature heat source for a local water/water heat pumps meeting the heating and hot water requirements. Table 5.8 shows the simulation results that have been obtained for such a new configuration, based on the network layout of configuration 1A1.

Before discussing the most interesting result given in Table 5.8, namely the required distributed energy for both configurations, a few explanations shall be given regarding the investment costs of the pipes and the circulation pump. The pipes for the new configuration are more expensive than for configuration 1A1, although in configuration 1A1 there are two supply and two return pipes whereas in the new configuration there is only one supply and one return pipe. The reason for this is that the total pipe diameter in the new configuration is larger than in configuration 1A1. The mass flow rates of water that circulate through the pipes in winter are indeed larger in the new configuration, because of the small temperature difference that can be achieved on the water from the lake circulating through the pipes (4°C,

		Configuration 1A1	New configuration
Investment costs CHF/year	HP3	349 632	0
	GE	190 444	0
	Pipes	192 121	231 142
	Heat exchangers	43 992	0
	Local heat pumps	0	109 225
	Circulation pump	5 624	18 370
	Total	**781 813**	**358 737**
Distributed energies kWh/year	Natural gas	10 623 130	0
	Electricity	2 149 130	3 967 514+4 200 420
Operating costs CHF/year		**704 311**	**1 061 831**
Total costs **mio-CHF/year**		**1.49**	**1.42**

Table 5.8: Comparison between a four-pipe system (configuration 1A1) and a two-pipe system (New configuration)

to avoid freezing). Just to mention one figure, the total mass flow rate leaving node 5 during the winter day period in configuration 1A1 amounts to 38.8 kg/s, whereas it amounts to 129.7 kg/s for the new configuration. This large amount of water that needs to be pumped is also reflected in the investment cost of the circulation pump. Less water could be pumped through the pipes in winter, if it was heated up to a certain temperature level by a large district heat pump at the plant for instance, and that the local water/water heat pumps only had to supply the energy to bring the water to the final requested temperature level. This opens a new field of two-pipes optimization problems representing an interesting direction for future work.

From Table 5.8 one can see that the total annual costs for both configurations are in the same range, and that the new configuration requires less distributed energy to meet all the energy services (the electricity required in the new configuration includes 3 967 514 kWh for the heat pumps and the circulation pumps, as well as 4 200 420 kWh for the electricity requirements, resulting in a total of 8 167 934 kWh for all energy services). Regarding the distributed energies, and in order to compare both configurations "fairly", the way how the electricity used in the new configuration is generated, should be included in the comparison. A cogeneration unit to produce this electricity might not be meaningful in the new configuration, if the heat cannot be valorized (since heat pumps meet all the requirements). Therefore, other technologies should be considered (gas turbine combined cycle without heat recovery and generating the electricity for more than just this district, hydro,...). Let us suppose, for instance, that a gas turbine combined cycle with an electric efficiency of 58% generates this electricity, the new configuration would require (8 167 934/0.58)=14 082 645 kWh of natural gas. At the same time, configuration 1A1 requires 10 623 130 kWh of natural gas for the gas engine, and would require another 3 705 396 kWh to generate the 2 149 130 kWh electricity (assuming the same electric efficiency of 58% as for the new configuration), resulting in a total of 14 328 496 kWh of natural gas (14 328 496 = 10 623 130+ 3 705 396). The difference between both configurations in this case would be about 2%, making both configurations more or less equal on an environmental point of view. This example demonstrates not only the importance stressed in Sections 1.5 to 1.7 to consider all the energy services together (and not separately), but also the importance of including the energy source in the comparison. Let's admit for instance that for the two configurations compared, the electricity was of hydraulic origin instead of coming from a combined cycle without heat recovery, the new configuration would be preferable to configuration 1A1 in terms of emissions.

5.4.2 Space restrictions

Developing district energy systems in existing cities can be made difficult due to the lack of available space in existing underground channels. An example shall be shown here to demonstrate how the slave optimizer integrates the constraint of space restriction and how this affects the result. Let us take the network shown on Figure 5.8. To compute this network, no space restriction was imposed, regarding the diameters of the pipes. The resulting diameter between node 5, where the district technologies are implemented, and node 11, is 63 mm for the heating network and 112.4 mm for the cooling network. Figure 5.18 shows the new resulting network when a maximum diameter of 10 mm is allowed between nodes 5 and 11 of the heating network. The slave optimizer has redesigned the configuration of Figure 5.8 diverting the network over nodes 12 and 10. Note that the size restriction on the pipe of the heating network also affects the cooling network (the shape of the cooling network is different between Figure 5.18 and Figure 5.8). This is logical since it is cheaper to have both networks running in parallel (only one gallery needs to be dug for both) than to have different routes for each network. For this new configuration, the investment costs for the network amount to 193 787 CHF/year (compared to 192 121 CHF/year for configuration 1A1), and 5 738 CHF/year for the pump (compared to 5 624 CHF/year for configuration 1A1). These increases are not dramatic due to the size of the problem (short distances), but nonetheless demonstrate the abilities of the slave optimizer.

5.4.3 Inhomogeneous requirements

For the test case analysed in the present chapter, the buildings are quite close to one another and the temperature levels for all the thermal energy requirements are the same for all buildings. It is therefore of no big surprise that with such a homogeneous district, all buildings are connected to the heating (and cooling) networks in clusters

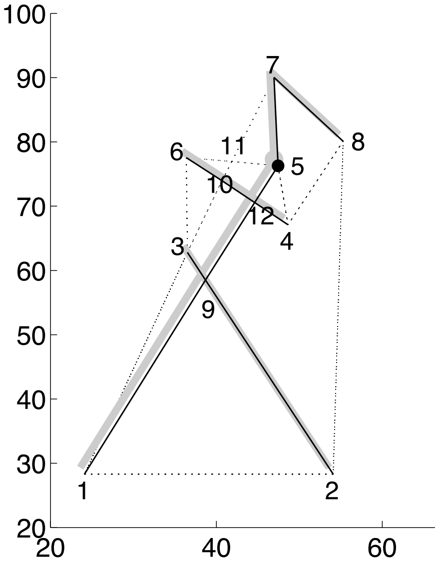


Figure 5.18: Resulting network from the slave optimization, with the same input from the master optimization as for configuration 1A1 but with a size restriction imposed between buildings 5 and 11

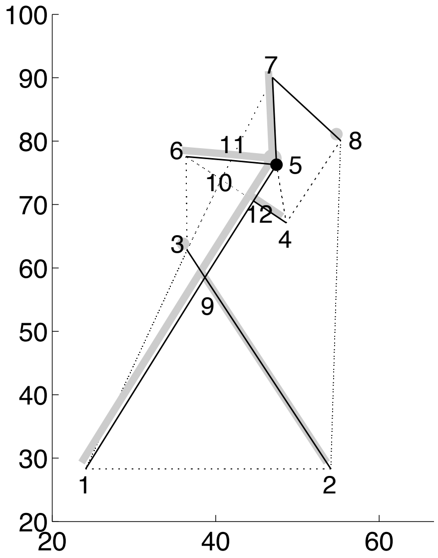


Figure 5.19: Resulting network from the slave optimization, with the same input from the master optimization as for configuration 1A1 but with buildings featuring requirements with different temperature levels

1 and 2. Figure 5.19 shows the resulting network for the same district, but with less homogeneous temperature levels. To compute the network of Figure 5.19, the slave optimizer got the same input from the master optimizer as for configuration 1A1, but with following changes regarding the temperature levels of the heating and hot water requirements:

- The supply and return temperatures for the heating requirements in buildings 3 and 8 have been increased for periods 5 and 6 (winter periods) from $T_S = 58°\text{C}$ to $T_S = 70°\text{C}$ and from $T_R = 48°\text{C}$ to $T_R = 55°\text{C}$.
- In buildings 1 and 2, the temperature levels for the hot water requirements have been decreased from 60°C to 40°C, which would be enough for buildings having no showers for instance (office buildings).

From Figure 5.19 one can see that since nothing changed for the temperature levels of the cooling requirements, the cooling network remains the same. However, the heating network does not serve buildings 3 and 8 anymore, which now have their own boilers (and not heat pumps, due to the high temperature levels).

5.5 Post-processing phase

Once the Pareto optimal frontier has been computed, the most interesting options in terms of CO_2 emissions and cost are known. In order to choose which configuration will finally be implemented, the decision makers have to perform a multi-criteria analysis which will be specific to their situation. For instance, if the priority is to decrease the CO_2 emissions, the least emitting configuration will be chosen. On the other hand, various "what if..." scenarios can now be tested. For instance, what happens if the price of the electricity from the grid increases due to new contracts with european partners and a general fear of electricity shortage? Or until what point would the centralized generation of heating and cooling still be an environmentally interesting solution, if the reverse individual heat pumps become popular? How much more are the consumers of a district willing to pay in order to get a more environmental friendly energy service provider? The answers to these questions will restrict the choice to a limited number of solutions which will then have to be refined with more detailed models, and why not a more accurate division of the year in periods.

Due to the politic and/or uncertain nature of the majority of the criteria that will play a role in the final choice of the solution, this topic will not be treated in further details at this stage, except for the gas price and the electricity mix which are taken up in the next chapter. It is however important to note that the Pareto optimal frontier as shown in this chapter offers a scientific basis for further discussion, and not the final solution for the district energy system to implement.

5.6 Conclusion

This chapter shows an example of the application of the DESD(OP)^2 method on a test case. It demonstrates the ability of the method to design and optimize a district energy system, showing the trade-offs between the costs and the CO_2 emissions for different configurations. The consideration of the temperature levels at which thermal requirements have to be satisfied, the simultaneous consideration of temporal and spatial (geographical) aspects, or else the possibility to exclude some buildings from the distribution network, are among the important features that the method is able to handle. This chapter however also revealed a major limitation of the method. From the results it appears that individual back-up chillers are never competitive when a lake can provide cooling "for free" in summer. However, due to the splitting of the requirements that can be met by each of the networks (the heating network meets the heating and hot water requirements and the cooling network meets the cooling requirements), and the fact that the two networks can exchange energy only at the plant (if a HP1 type heat pump is implemented that connects both networks), solutions for which a cooling network used in summer can be used as heat source for individual water/water heat pumps in winter are excluded. This last point represents an important topic for a future development of the method.

Chapter 6

Geneva case study

6.1 Introduction

In this chapter a real case is presented by means of an example taken from the Canton of Geneva (Switzerland). This case was studied in the frame of a more global project for which the goal was to define different scenarios to provide the whole region with the four main energy services by the year 2050. This project was ordered by the Public Utilities of Geneva. The goal of this chapter is to demonstrate the ability of the method to deal with problems featuring very different sizes. In the case analysed here, the buildings of the previous chapters are replaced by entire sectors aggregating the energy requirements of many buildings. Therefore, unlike the previous chapter, in which the nodes represented buildings with a heat-exchanger between the network(s) and the buildings, in this chapter the nodes represent network sub-stations, that get the energy from the main distribution network(s) before redistributing this energy inside the sector. As a result, compared to the previous chapter in which the focus was set on the satisfaction of the energy requirements of every single building, in this chapter the goal is to define an energy system for a whole region, ensuring the satisfaction of the energy requirements of whole sectors. As a consequence, the district energy system optimized in this chapter will include the plant, the sectors and the main distribution network(s) but not the redistribution from the sub-stations to the end-users (buildings). Besides, since the required information regarding the consumption profiles, as well as the required temperature levels for the thermal energy requirements, are often missing or incomplete, this chapter indicates different sources of information that can be useful to establish these profiles. Like in Chapter 5, the structure of the present chapter follows the structure of the method as depicted on Figure 2.1.

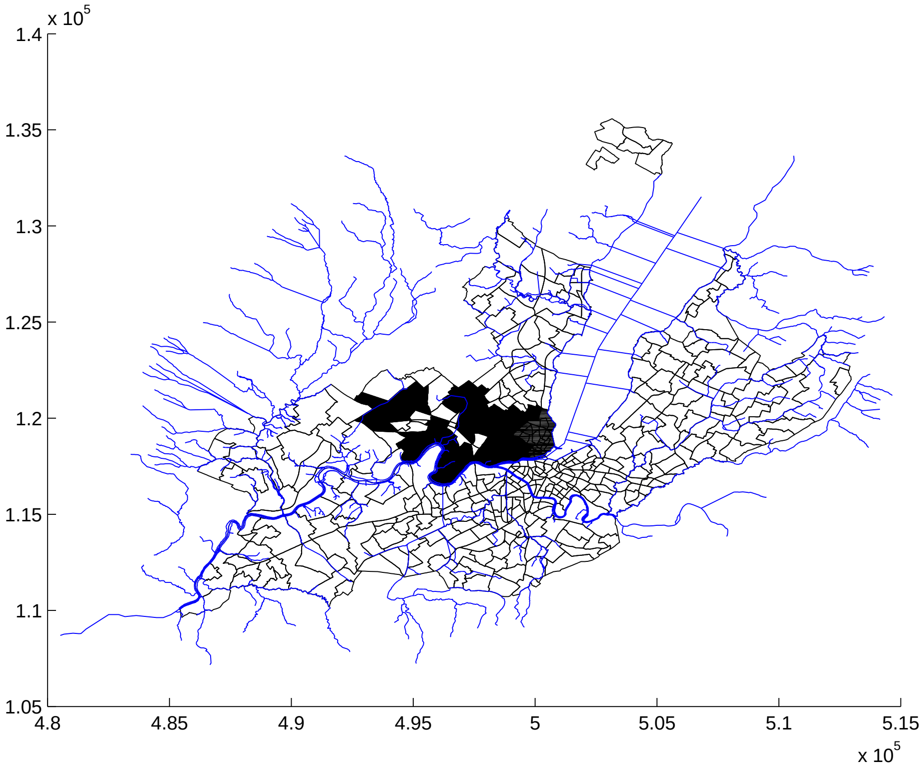
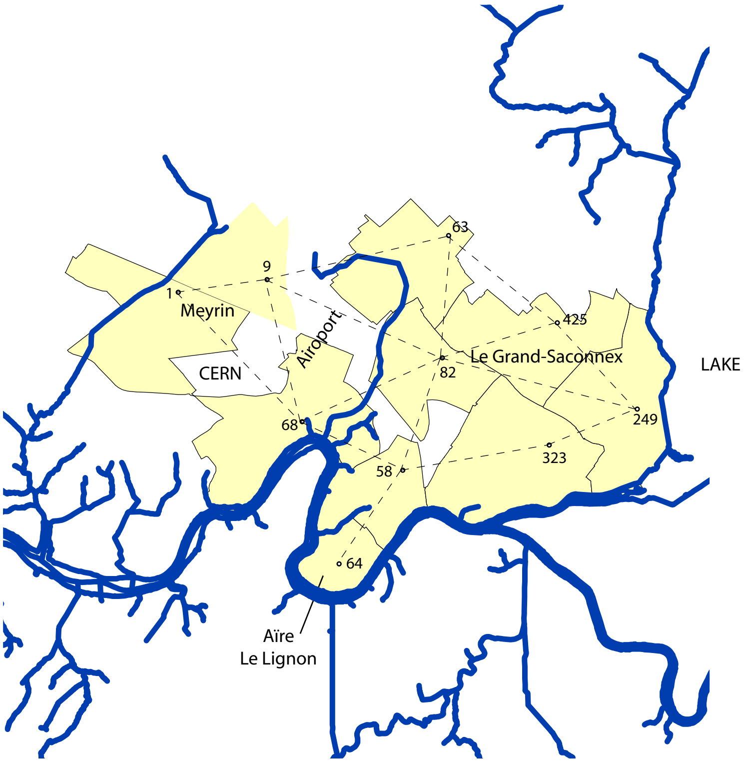


Figure 6.1: Part of the Canton of Geneva considered in the study

6.2 Description of the case and structuring of the information

The case presented here is characterised by large energy requirements for a whole region. The method is therefore used to design a district energy system that will feed sub-stations. The region is divided into sectors as shown on Figures 6.1 and 6.2. This region is delimited by the CERN (the European Organization for Nuclear Research), the International Airport of Geneva, the municipality of Grand-Saconnex, the Lake of Geneva and the River Rhône (the dotted lines on Figure 6.2 represent the allowed connections for the network(s) and *not* existing pipes). The population of the region represents approximately 50 000 inhabitants. The goal for this case study was to make a first investigation to analyse the viability of the production of electricity using a gas turbine combined cycle with municipal heat recovery, and not to define the detailed configuration of the network to every single customer. It represents therefore a good example of how the method can be applied for preliminary studies, and/or for cases where the choice of the district energy conversion technology is partly imposed (gas turbine combined cycle).



	Heating kWth	Hot water kWth	Cooling kWth	Electricity kWel
1	17 355	902	2 300	4 410
9	15 722	1 291	524	3 292
58	11 767	841	1 000	2 617
63	5 578	329	933	4 344
64	2 165	148	113	590
68	8 344	654	550	2 176
82	14 401	1 123	921	3 285
249	54 034	4 584	6 392	13 510
323	71 914	5 878	3 940	14 957
425	19 478	1 543	2 125	4 487

Figure 6.2: District analysed, with the maximum average hourly requirement rates in kW for each energy service

Parameter	Unit	Summer	Mid-season	Winter
Temperature of the Rhône	°C	14	9	6
Temperature of the municipal wastewater treatment facility in summer [10]	°C	22	18.5	16

Table 6.1: Temperature level of the River Rhône and the wastewater treatment facility

LIST OF AVAILABLE ENERGY SOURCES

Regarding the renewable energy sources, the municipal wastewater treatment facility represents an important source. The potential from the municipal waste incineration plant is already exploited for another area of the Canton. The Lake of Geneva and the different rivers (especially the River Rhône) also represent major sources of energy. However, since one of the constraints was the location of the plant on nodes 64 or 68 (proximity to the wastewater treatment facility), the use of the lake has been relinquished in favour of the Rhône. Wind is not an option in Geneva. If the wind can indeed blow very heavily in this region, it is not in a continuous manner at all, making the use of windmills economically nonviable. Biomass could be an option, but was not investigated in this preliminary study since the currently available biomass is too small to satisfy the demands of the region (180 GWh of biomass [10] compared to the demands that amount to 590 GWh). Regarding the non renewable sources, natural gas is the only one that is considered, since heating oil has been left out except for individual back-up boilers. The available energy sources are therefore:

1. river Rhône and other smaller rivers,
2. wastewater treatment facility,
3. natural gas.

The temperature levels for the river Rhône and the wastewater treatment facility are given in Table 6.2.

ENERGY CONSUMPTION PROFILES WITH POWER AND TEMPERATURE LEVELS

Since no consumption profiles were available for any of the energy services, they had to be computed on the basis of data and information collected from different sources. A method was developed on purpose by Girardin [47]. The types of information that can been used when no profiles are available are shown in Section 6.3. At this stage it is only important to know that the year has been divided into six periods having the durations given in Table 6.2, together with T_t^{ext} the average outside temperature during the period. Moreover, the maximum average hourly energy rates, summed over all buildings, amount to 220 758 kW for heating, 17 293 kW for hot water, 6 482 kW for cooling and 53 668 kW for electricity. The order of magnitudes are thus one to two order(s) larger than the ones of the test case of the previous chapter (3 640 kW for heating for instance).

Period	Duration	T_t^{ext}
Summer day	1095	25
Summer night	1095	15
Mid-season day	2190	18
Mid-season night	2190	10
Winter day	1095	1
Winter night	1095	-5

Table 6.2: Duration and T_t^{ext} for each period

List of possible district energy conversion technologies

Following the list of available energy sources, the high levels of energy requirements, and the constraints that the Canton wants to generate part of its electricity with a gas turbine combined cycle, the following technologies have been considered for heating, hot water and electricity (with their lower and upper bounds):

1. Natural gas turbine combined cycle (NGCC), 20-100 MWel: the limit of 100 MWel corresponds to the maximum size that can be implemented in this well populated area.
2. HP1 (1-20 MWth): uses the return of the cooling network as a heat source.
3. HP2 (1-20 MWth): uses the River Rhône as a heat source.
4. HP3 (1-20 MWth): uses the municipal wastewater treatment facility as a heat source.

Regarding the heat pumps, several 20 MW large heat pumps can of course be implemented in parallel if such a solution happens to be promising.
For cooling HP1 and cooling with water from the River have been considered.

Spatial constraints

Due to the nature of the case study (preliminary investigation), no special constraints were imposed as for the pipes and the configuration of the network. The allowed connections, on Figure 6.2, have been determined, considering more or less all the elementary meshes. If it is indeed important at the stage of a preliminary study not to include connections that obviously don't make sense (like for instance connection 64-68 and vice-versa, that would cross two times the relatively large River Rhône), it is not advisable either to go into the details of following every single road. The connections crossing the smaller rivers have therefore been allowed at this stage of the investigation. As already mentioned, nodes 64 and 68 have been pre-selected to implement the district energy conversion technologies. These nodes are indeed close to the the wastewater treatment facility, which has been chosen as energy source.

Individual back-up technologies

As back-up energy conversion technologies, for heating and hot water, boilers and water/water heat pumps, have been considered. Considering the level of the ther-

Parameter	Value	Units	Reference
Exergetic efficiency of the individual back-up water/water heat pumps	0.6	[-]	[47]
Exergetic efficiency of the individual back-up chillers	0.19	[-]	after [27] (note: This value has been mistakenly computed too low, but fortunately doesn't affect the result dramatically)

Table 6.3: Values of the parameters related to the individual back-up technologies, used in the optimization phase of the Geneva case

mal energy requirements (several MWth), and the fact that the nodes represent sub-stations and not buildings, air/water heat pumps were not considered. Therefore, since water is very much present all over the area (lake of Geneva, River Rhône and many smaller rivers), it was assumed that water/water heat pumps could be implemented not only for nodes where the temperature level of the distribution network should be increased, but also for nodes which are not connected to the heating network. Regarding cooling, it was likewise assumed that the energy extracted by the chillers from the buildings could be released in the rivers, and not in the air. The costing and efficiency parameters for these devices are given in Table 6.3 and 6.4.

6.3 Energy requirements profiles

In this section, the type of information that can be used when no energy consumption profiles are available, is briefly pictured. These information are summarized in Table 6.5 and explained hereunder. The method developed by Girardin [47] to compute the energy consumption profiles is given in Appendix A.4.

YEAR OF CONSTRUCTION OR RENOVATION OF THE BUILDING
The year of construction is important to evaluate the quality of the insulation. The following periods have been defined in the present case study: up to 1920 (included), between 1920 and 1970 (included), between 1970 and 1980 (included), and from 1980.

ALLOCATION OF THE BUILDING
The allocation of the buildings helps defining the type of comfort requested by the users. The following allocations have been defined: residential, offices, shops and supermarkets, industry, schools and universities, hospitals, hotels, others (sport facilities,...).

FUEL (OIL OR GAS) CONSUMPTION OF THE BUILDING
In case the building has a boiler, the total fuel consumption of a given building k, R_k^{fuel}, corresponds to the total heating and hot water requirements, divided by the thermal efficiency of the boiler. It allows to calculate the integration of the average hourly energy rate over the time to compute the total energy required.

Parameter	Range	Value	Unit	Reference
C_{fix}^{pipe}	300-500 mm ø	544	CHF	[26]
c_{prop}^{pipe}	300-500 mm ø	5 032	CHF/m	[26]
C_{fix}^{boiler}	≥5 000 kWth	1 000	CHF	[26]
c_{prop}^{boiler}	≥5 000 kWth	45	CHF/kWth	[26]
C_{fix}^{pump}	≥10 kW	8 554	CHF	[26]
c_{prop}^{pump}	≥10 kW	202	CHF/kWth	[26]
C_{fix}^{ww}	2 500-20 000 kWth	4 000 000	CHF	[75]
c_{prop}^{ww}	2 500-20 000 kWth	419	CHF/kWth	[75]
C_{fix}^{chiller}	500-5 000 kWth	871 600	CHF	Eval. after [75]
$c_{prop}^{\text{chiller}}$	500-5 000 kWth	500	CHF/kWth	Eval. after [75]
r		0.08		[37]
r^i	$i = aw, boiler, chiller, hex, pipes, pump, ww$	0.08		[37]
F_m^i	$i = aw, boiler, chiller, pipes, pump, ww$	0.06		[37]
M_S^i	year 2006 ($i = aw, boiler, chiller, ww$)	1306.6		[37]
M_S^i	year 1998 ($i = hex, pipes$)	1306.6		[37]

Table 6.4: Parameters for the costing functions in the Geneva case study

FLOOR SURFACE OF THE BUILDING

The floor surface of a building k, SRE_k, corresponds to the total heated surface of the building. In other words to the footprint of the building multiplied by the number of floors which are being heated (usually all the floors except eventually the basement).

ENERGY SIGNATURE

The energy signature of a building k, represents the heating requirements of this building, $\dot{Q}_{H,t,k}^{\text{cons}}$, as a function of the daily average outside temperature T_t^{ext}. Examples of energy signatures for some buildings included in the analysed region are given in Figure 6.3. The temperature at which the slope crosses the X-axis is the daily average temperature above which no heat is provided to the building anymore. The energy signature is defined mathematically following Equation 6.1, with $T_{H,k}^{dimen}$ the temperature for which the heating system has been designed (usually -6°C in Geneva), and $\dot{Q}_{H,k}^{\text{dimen}}$ the design size of the heating equipment. Phisically, the slope $s_{H,k}$ corresponds to the heat losses of the building, which are directly proportional to the outside temperature.[1]:

$$\dot{Q}_{H,t,k}^{\text{cons}} = -s_{H,k} \cdot (T_t^{\text{ext}} - T_{H,k}^{dimen}) + \dot{Q}_{H,k}^{\text{dimen}} \tag{6.1}$$

---

[1] The design size of the heating equipment that would have to be implemented in building k, includes the heat gain from the electric devices, the persons and the sun [84]. In the case of district heating, $\dot{Q}_{H,k}^{\text{dimen}}$ corresponds to the energy that the heat exchanger between the network and the building must be able to transfer.

Data			Source
Building coordinates	[° ’ ”]		Geographical information system of the Canton of Geneva (SITG)
Year of construction or renovation of the building	[year]		Geographical information system of the Canton of Geneva (SITG)
Allocation of the building	[-]		Geographical information system of the Canton of Geneva (SITG)
Fuel (oil or gas) consumption of the building	[MJ/year]	R_k^{fuel}	Energy Service of the Canton of Geneva (Scane)
Floor surface of the building	[m^2/build]	SRE_k	Office of Statistics of the Canton of Geneva (OCSTAT)
Energy signature of the building as a function of the outside temperature	[kW]		City of Geneva
Meteorological data	[-]		MeteoSwiss
Boiler efficiency	[-]	ϵ^{boiler}	Bonnard et Gardel Consultants
Temperature levels at which the heating, hot water and cooling requirements have to be met in the building	[-]	$T^{cons}_{H,t,k}$ $T^{cons}_{HW,t,k}$ $T^{cons}_{C,t,k}$	Bonnard et Gardel Consultants

Table 6.5: Data provided by different offices to compute the requirements profiles

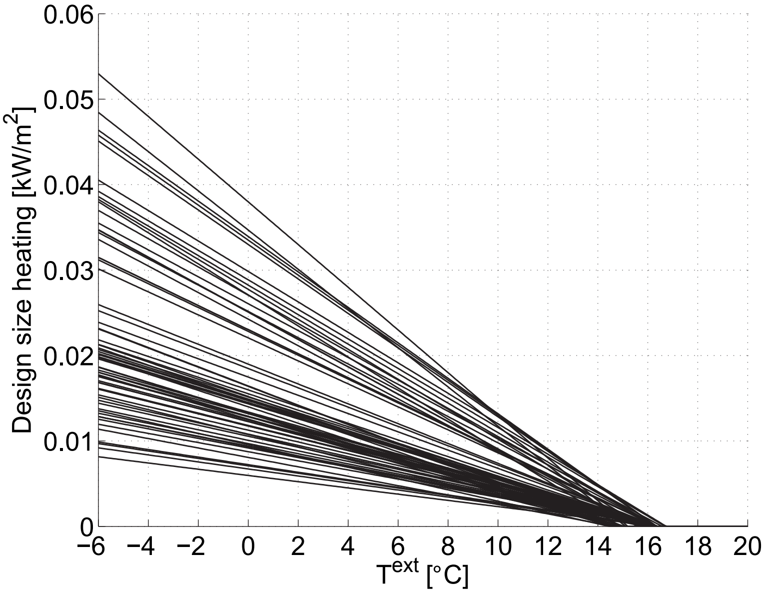


Figure 6.3: Examples of energy signatures for buildings in the Canton of Geneva [47]

When all the information listed above are available at least for a few buildings, which was the case for the Geneva case study, the heating and hot water consumption profiles for all the other buildings can be evaluated according to the method developed by Girardin [47] and explained in Appendix A.4.

For the cooling requirements the statistical data being much more scarse than for heating, following assumptions were made:

1. The temperature below which no cooling is provided anymore has been set to 12°C.
2. The cooling energy amounts to 10% of the heating energy.
3. Cooling is provided only during the summer periods (no computer room cooling, for instance during the mid-season periods, was considered).

For the electricity requirements, average values published in [84], given for the different types of allocations, were used.

Finally, knowing the energy requirements profiles for heating, hot water, cooling and electricity for each building, and the types and numbers of buildings in each sector (thank to the allocations and coordinates of the buildings), aggregated energy requirements profiles as well as composite curves for each node have been computed. These requirements profiles are shown in Figures 6.4 to 6.7, and an example of composite curves for the heating and hot water requirements during each day period is given in Figure 6.8 (sector/node 323).

The temperature levels for the heating requirements, have been set on the same basis as in Chapter 5 for all sectors, namely: $T_S = 35°\text{C}$ and $T_R = 32°\text{C}$ for the mid-season periods and $T_S = 58°\text{C}$ and $T_R = 48°\text{C}$ for the winter periods for heating, $T_S = 18°\text{C}$ and $T_R = 21°\text{C}$ for cooling, and finally the required temperature level for hot water equals 60°C.

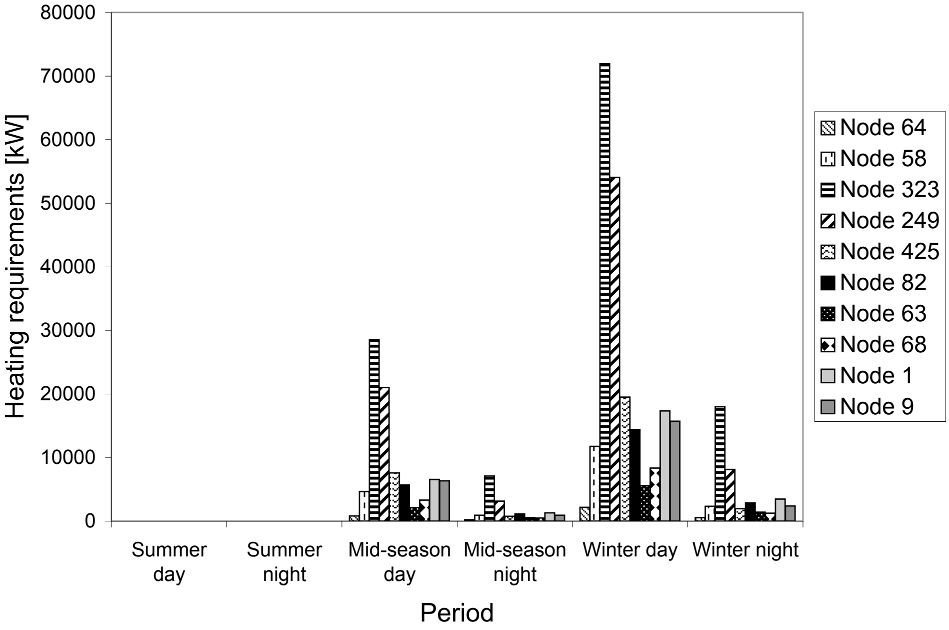


Figure 6.4: Heating requirements profile

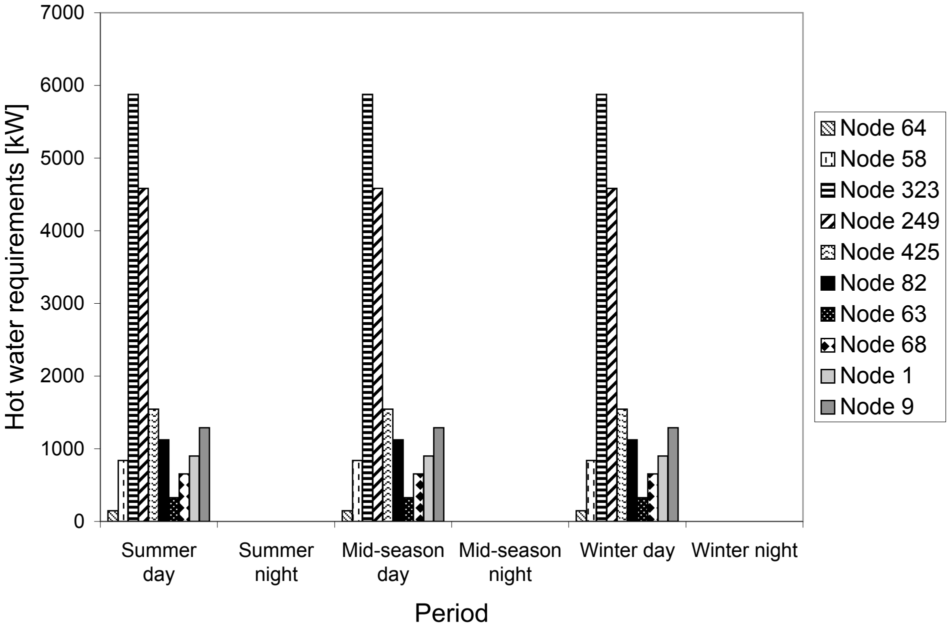


Figure 6.5: Hot water requirements profile

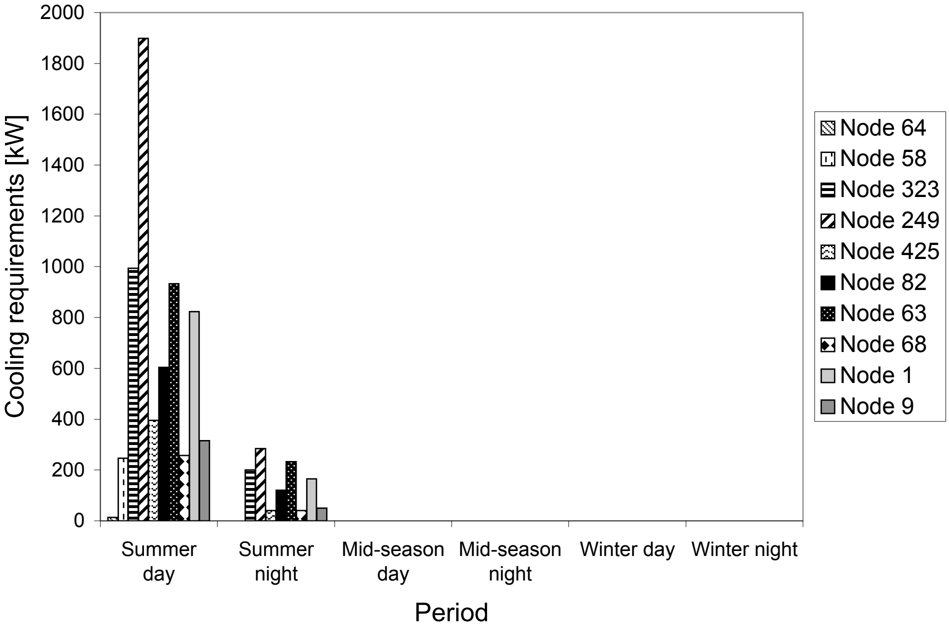


Figure 6.6: Cooling requirements profile (The same observation as in Figure 5.5 can be done regarding cooling requirements during the summer night period, when the atmospheric temperature is below the supply and return temperatures of the internal circuit in the building.)

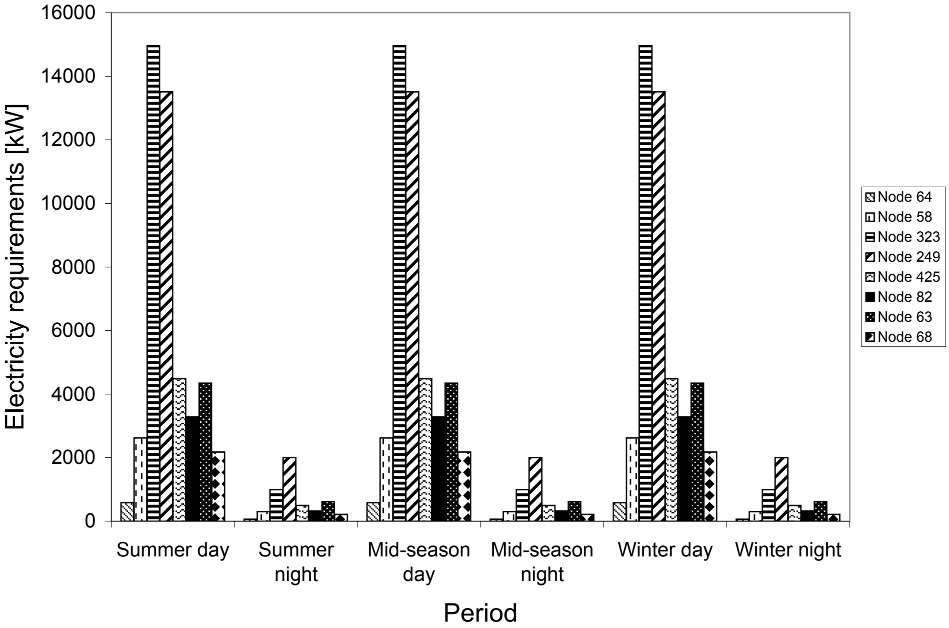


Figure 6.7: Electricity requirements profile

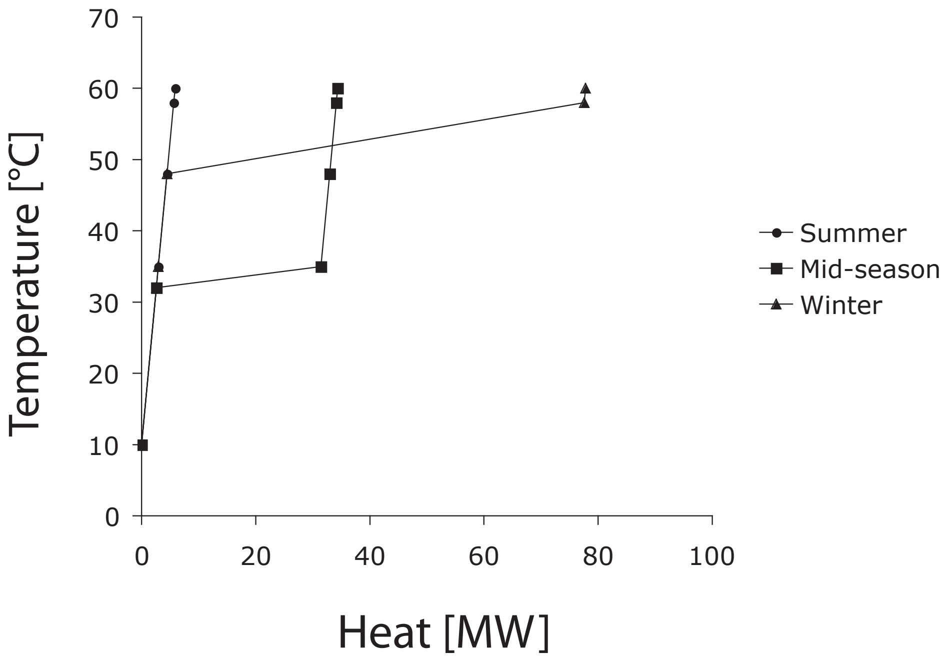


Figure 6.8: Composite curve for the heating and hot water requirements of sector (node) 323 for the day periods

6.4 Optimization phase

6.4.1 Decision variables

For the district analysed in this chapter, and following the list of selected district energy conversion technologies that are reasonable for this case, the master optimizer optimizes the following 15 decision variables:

1. Supply and return temperatures of the heating network in summer, and winter/mid-seasons: variables 1 to 4
2. Investment or not in a HP1, HP2 and HP3 as well as combined cycle gas turbine CCGT: variables 5 to 8
3. Design size of heat pumps HP1, HP2 and HP3 as well as combined cycle gas turbine CCGT: variable 9 to 12
4. Condenser temperature of heat pumps HP1, HP2 and HP3: variable 13 to 15

Regarding the supply and return temperatures of the cooling network, following the conclusions from the previous chapter that in a Pareto optimal configuration the supply temperature will be the minimum possible temperature, and the return temperature the maximum possible temperature, these temperatures have not been optimized in the present case study. They have been set directly to 14°C for the supply temperature (assuming direct circulation of water from the River Rhône in the pipes), and to 19°C for the return temperature (19°C equals the return temperature of the hydronic circuits in the buildings, minus the minimum temperature difference of 2°C). Besides, since the minimum part load of 20% admitted in Chapter 5 for the district heat pumps resulted in heat wasted to the surroundings for configuration 1A1 (Figure 5.10), this value was decreased to 5%. This is reasonable in the present case study as the high level of requirements compared to the size limit of 20 MWth for the heat pumps presupposes that several heat pumps will be implemented, and that it will therefore be possible to have relative fine tuning possibilities. The reason for not setting this value directly to 0 is to prevent the slave optimization from operating the heat pumps at senseless small part loads. Beside, remember that if a HP3 type heat pump is implemented, it will be divided in a HP3a and a HP3b heat pump in order to make a better use of the large temperature difference that can be extracted from the wastewater. Finally, remember that the master optimization also defines the CO_2 weighting factor that is merely a mathematical decision variable, in order to take into account the objective *CO_2 minimization* in the slave optimizer.

All the parameters used for the Geneva case are given in Tables 5.5, 6.4 and 6.3 (regarding the parameters of the district energy conversion technologies, please refer to the model descriptions, Section 4.3).

6.4.2 Conditions defined for the optimization and resolution phase analysis

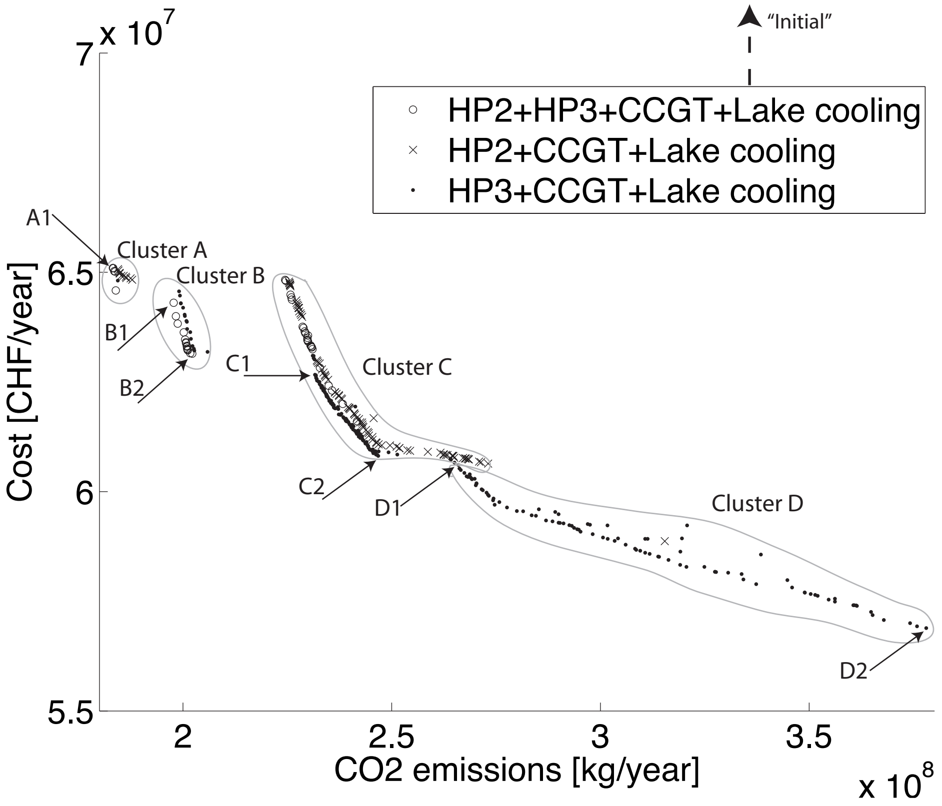
Like in the previous chapter, the superfluous electricity could be sold for 0.09 CHF/kWh, and the avoided CO_2 has not been taken into account.

Unlike previous chapter, no tolerance was set for Cplex, so that the slave optimization returned the solution to the master optimization when it had reached optimality. The experience showed that the resolution time for the slave optimization is indeed smaller for the Geneva case study than for the test case. One reason for this is the smaller number of sectors (nodes) (12 for the test case versus 10 for the Geneva case). Like for the case analysed in Chapter 5, the exact number of variables optimized by the slave optimizer is dependant on the values of the variables given by the master optimizer.

The results of the optimization have been obtained after 15 800 iterations of the master optimization, and 24 hours and 23 minutes of computation time on 6 Intel Pentium4 2 800 MHz computers [76].

6.4.3 Results

The results of the optimization are shown on the Pareto optimal frontier on Figure 6.9. The detailed results for the most interesting configurations are given in Table 6.6. The least emitting configuration (A1) emits 183 228 tons-CO_2/year and costs 65.1 mio-CHF/year, whereas the configuration with the lowest costs (D2) emits



Configuration	Relative costs
"Initial"	100%
A1	76.0%
B1	75.1%
B2	73.7%
C1	73.1%
C2	71.0%
D1	70.9%
D2	66.5%

Figure 6.9: Pareto optimal frontier for the Geneva case study computed with the cost parameters given in Tables 5.5 and 6.4, and relative costs of each configuration compared to the "Initial" configuration (boilers for heating and hot water, electric chillers for cooling and electricity from the grid)

378 007 tons-CO_2/year and costs 56.9 mio-CHF/year (see Table 6.6). Note that for the Geneva case, the configuration "Initial" featuring only boilers, electric chillers and electricity from the grid, would emit 335 458 tons-CO_2/year and cost 85.6 mio-CHF/year, thus spreading the range of the axes in Figure 6.9. The following important comments can be made when looking at the Pareto optimal frontier:

1. Four main clusters (A to D) can be recognised, that each contain different

types of configurations.

2. Three different configurations, or combinations of district energy conversion technologies, can be found on the Pareto curve
    (a) a combination including a HP2 and a HP3 type heat pumps as well as a combined cycle[2], and district cooling with water from the River Rhône,
    (b) a combination including only a HP2 type heat pump together with a combined cycle, and district cooling with water from the River Rhône,
    (c) a combination including only a HP3 type heat pump together with a combined cycle, and district cooling with water from the River Rhône.
3. No configuration includes a HP1 type heat pump.

One important point to notice is that *all* configurations implement heat pumps, thus emphasizing the role played by heat pumps when designing district energy systems. In clusters A and B, the configurations including both heat pumps HP2 and HP3, perform better both in terms of emissions and in terms of cost than the other configurations. Besides, when only one type of heat pump is implemented, the configurations featuring a HP3 heat pump perform better than the configurations featuring a HP2 heat pump. These matter of facts are not surprising. The implementation of both types of heat pumps in series allow a better overall annual COP. Besides the evaporator temperature for HP3 heat pumps is higher than for HP2 heat pumps, allowing for better COPs. The best way to analyse the different clusters (A to D) is to look at the networks shown in Figures 6.16 and 6.17, as well as the composite curves given in Figures 6.10 to 6.15. The first important point to mention is that the different clusters do not differ in the number of buildings connected. Figures 6.16 and 6.17 are indeed representative of all the configurations appearing on the Pareto curve in that the sectors 249 and 323 always implement their own water/water heat pumps for the heating and hot water requirements, and their own chillers for the cooling requirements. These two sectors not only feature the largest heating and hot water requirements, but are also located far away from the plant as compared to other sectors. Besides, by limiting the size of the gas turbine combined cycle to 100 MW, the total size of the central heat pumps, and therefore the total amount of heat that can be delivered by the network, is implicitly also limited. The combination of heat pumps with a combined cycle are indeed interesting when all the energy conversion technologies can be put in series, like for instance during the winter day period (period 5) in Figure 6.10. If the proportion of heat delivered by the central heat pumps is not in adequation anymore with the heat that can be delivered by the combined cycle (in other words if the heat delivered by the combined cycle is not sufficient to finish the heating up of the water from the network, started by the heat pumps), there is no interest in implementing larger central heat pumps. This is particularly true when dealing with large energy requirements like in this case study, for which the decentralised heat pumps feature the same exergetic efficiency than the central (district) heat pumps (not mentioning the fact that by implementing decentralized heat pumps with good exergetic efficiencies for sectors 249 and 323,

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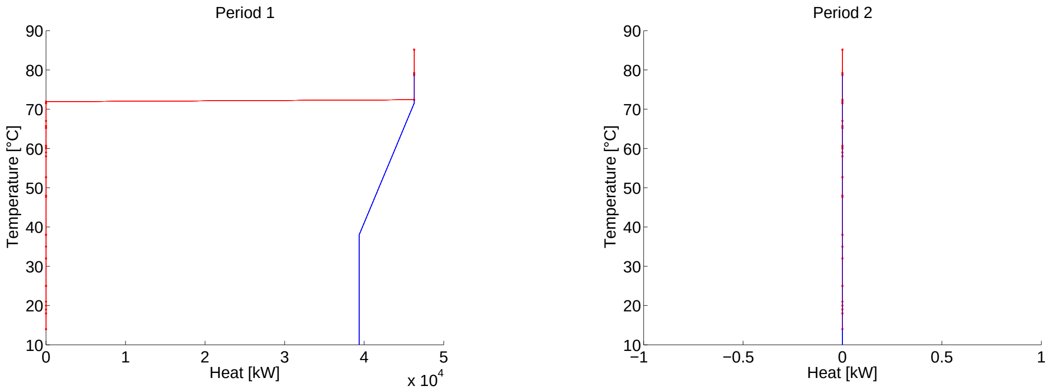
[2] Remember that the condenser temperature at which heat is released to the heating network equals the winter supply temperatures of the heating network plus a ΔT of 2°C.

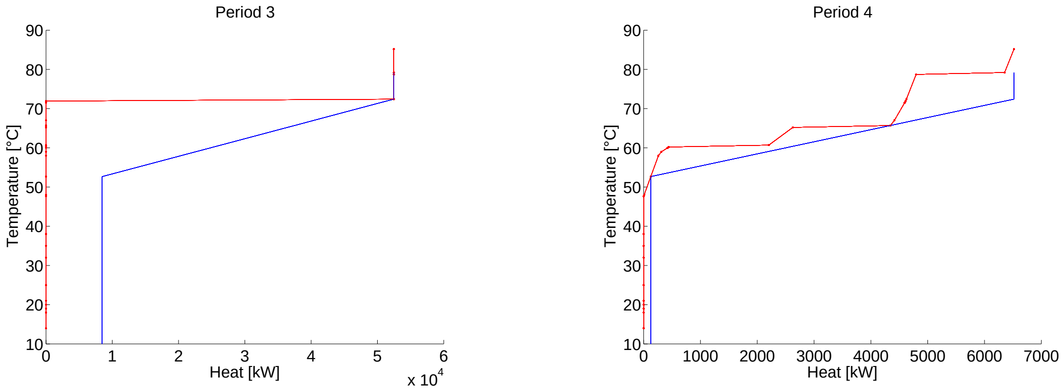
Configuration	A1	B1	B2	C1	C2	D1	D2
Annual CO_2 emissions ton-CO_2/year	183 228	197 765	202 239	231 852	246 813	264 068	378 008
Annual costs mio-CHF/year	65.1	64.3	63.1	62.6	60.8	60.7	56.9
Income I^{el} mio-CHF/year	0	2.9	3.7	9.3	12.2	15.8	38.5
Grid mio-CHF/year	12.4	14.3	9.8	12.9	6.8	9.4	2.6
Gas mio-CHF/year	24.4	25.8	29.3	32.6	38.9	40.3	64.3
Percentage Investment	43	40	42	37	37	35	30
Operational	57	60	58	63	63	65	70
HP2 Size MWth	25.5	3.5	3.1	0	0	0	0
Inv. mio-CHF/year	1.48	0.50	0.47	-	-	-	-
T_{cond} °C	79.2	87.4	87.0	-	-	-	-
COP summer	2.90	2.67	2.68	-	-	-	-
COP mid-season	2.71	2.52	2.53	-	-	-	-
COP winter	2.61	2.43	2.44	-	-	-	-
HP3a Size MWth	14.4	29.0	23.1	28.8	24.5	26.9	17.9
Inv. mio-CHF/year	0.84	1.69	1.35	1.68	1.43	1.57	1.04
T_{cond} °C	60.7	63.3	64.0	63.4	62.8	63.0	69.7
COP summer	3.82	3.67	3.63	3.67	3.70	3.69	3.35
COP mid-season	3.58	3.45	3.42	3.45	3.47	3.47	3.17
COP winter	3.43	3.31	3.28	3.31	3.33	3.33	3.06
HP3b Size MWth	14.4	29.0	23.1	28.8	24.5	26.9	17.9
Inv. mio-CHF/year	0.84	1.69	1.35	1.68	1.43	1.57	1.04
T_{cond} °C	65.7	68.3	69.0	68.4	67.8	68.0	74.7
COP summer	3.88	3.73	3.69	3.72	3.75	3.74	3.40
COP mid-season	3.64	3.50	3.47	3.50	3.53	3.52	3.22
COP winter	3.48	3.36	3.33	3.36	3.38	3.38	3.10
CCGT Size MWel	79.0	65.0	77.2	62.3	76.6	69.6	99.0
Inv. mio-CHF/year	14.1	12.4	13.7	12.2	13.7	12.9	15.8
ϵ_{el} %	53.3	52.8	53.3	52.6	53.2	52.9	54.0
ϵ_{th} %	36.7	37.2	36.7	37.4	36.8	37.1	36.0
River cooling kWth	8466	8466	8466	8466	8466	8466	8466
Network Inv. mio-CHF/year	2.9	2.7	2.7	2.8	2.7	2.7	2.7
Pumps Inv. CHF/year	64 001	58 807	60 139	61 399	59 280	58 682	57 769
Back-up (heat) Inv. mio-CHF/year	7.03	7.03	7.03	7.03	7.03	7.03	7.03
Back-up (cool) Inv. mio-CHF/year	0.75	0.75	0.75	0.75	0.75	0.75	0.75
$T_{\mathrm{hs},t}$ °C Summer	71.5	73.9	85.7	71.2	75.6	69.1	71.6
Mid-season and winter	72.4	80.4	80.7	74.9	79.6	80.5	87.8
$T_{\mathrm{hr},t}$ °C Summer	38.0	52.5	62.4	50.2	51.8	48.2	51.3
Mid-season and winter	52.7	50.8	54.3	50.9	51.1	50.5	55.4
$T_{\mathrm{hs},t} - T_{\mathrm{hr},t}$ °C Summer	33.5	21.4	23.3	21.0	23.8	20.9	20.3
Mid-season and winter	19.7	29.6	26.4	24.0	28.5	30.0	32.4

Table 6.6: Main configurations for the Geneva case, with the values given in Tables 6.4 and 5.5. As a comparison, configuration "Initial", not shown in the table, implementing boilers and electric chillers and taking electricity from the grid, emits 335 458 tons-CO_2/year and costs 85.6 mio-CHF/year. (The annual costs are given after deduction of the income resulting from the electricity sales. Therefore, to compute the percentage of investment and operational costs, this income is added up again to the total costs.)



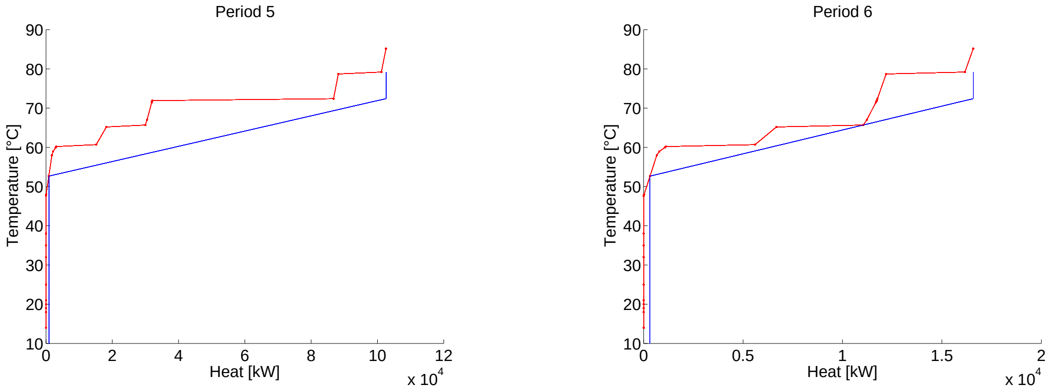
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

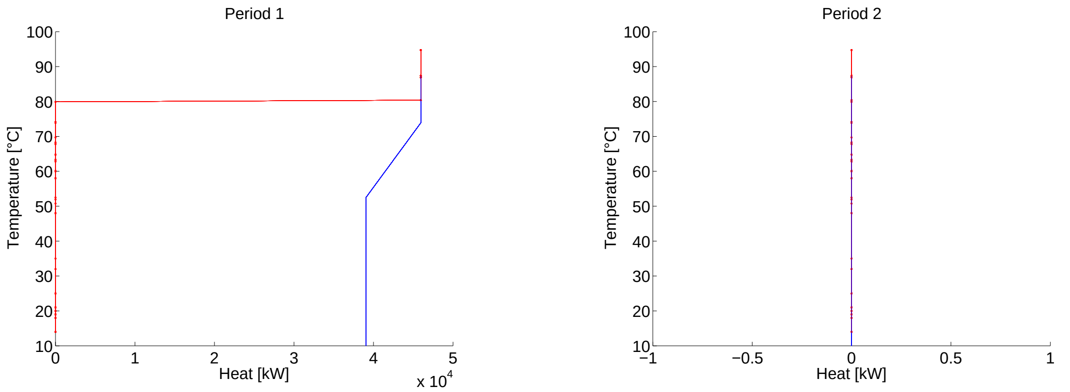
Composite curve of the mid-season night period



Composite curve of the winter day period

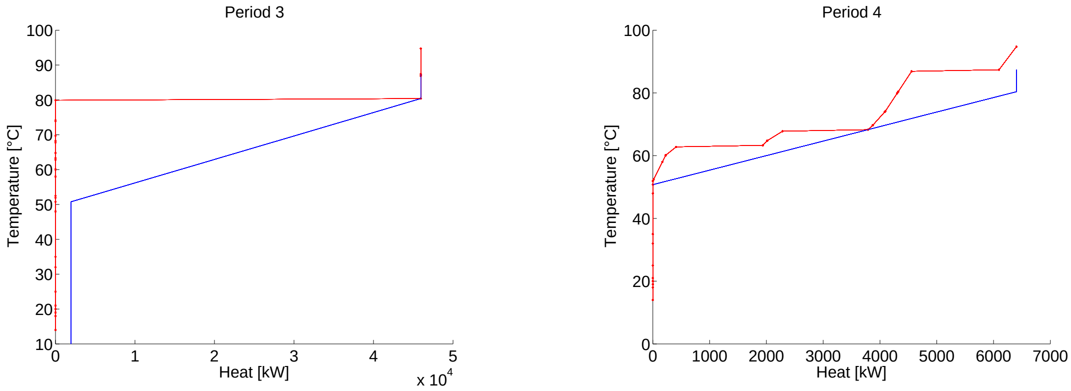
Composite curve of the winter night period

Figure 6.10: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration A1 (see Figure 6.9 and Table 6.6)



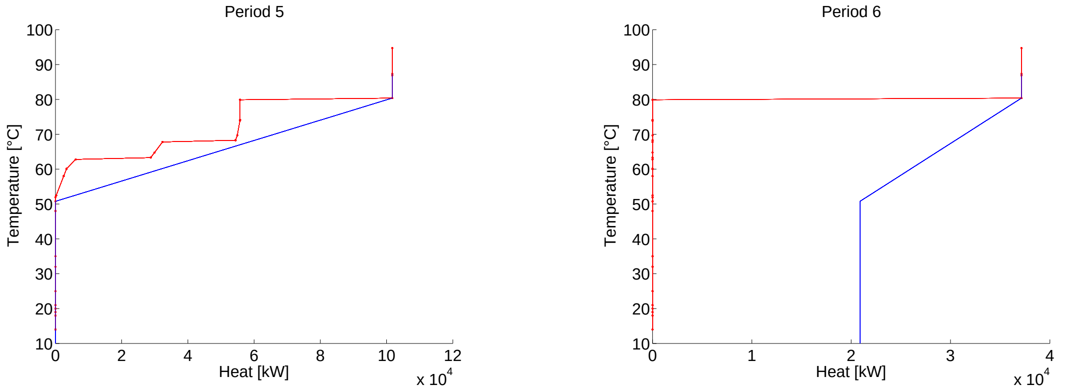
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

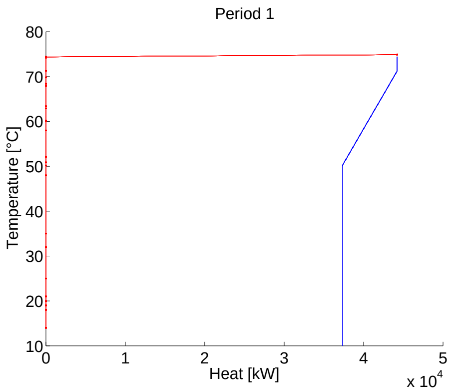
Composite curve of the mid-season night period



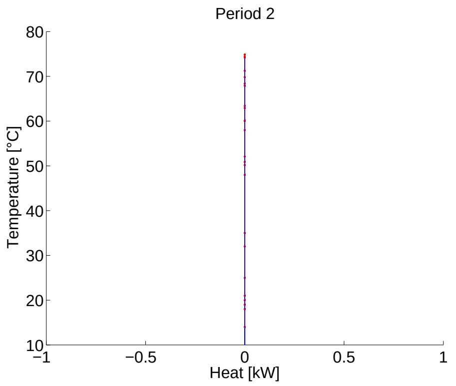
Composite curve of the winter day period

Composite curve of the winter night period

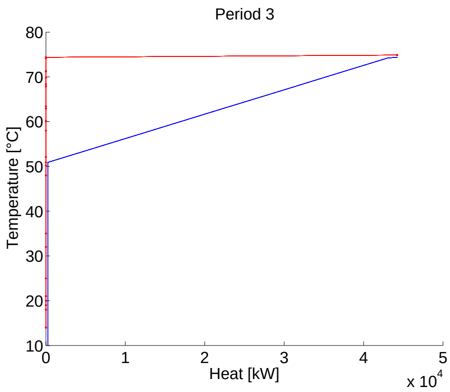
Figure 6.11: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration B1 (see Figure 6.9 and Table 6.6)



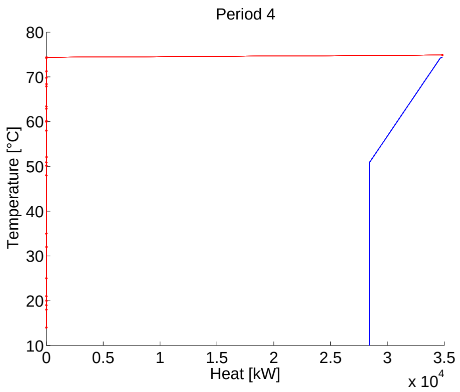
Composite curve of the summer day period



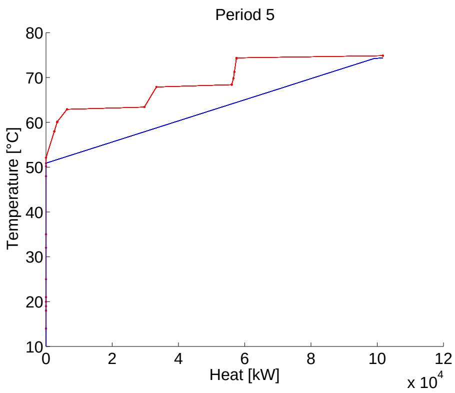
Composite curve of the summer night period



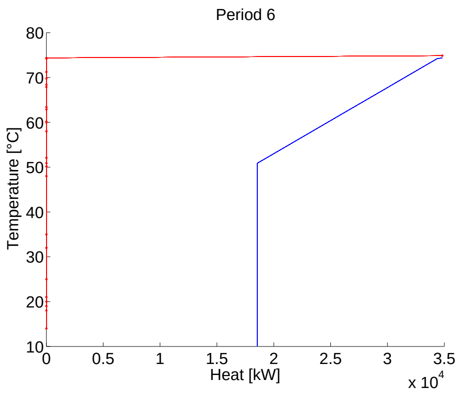
Composite curve of the mid-season day period



Composite curve of the mid-season night period

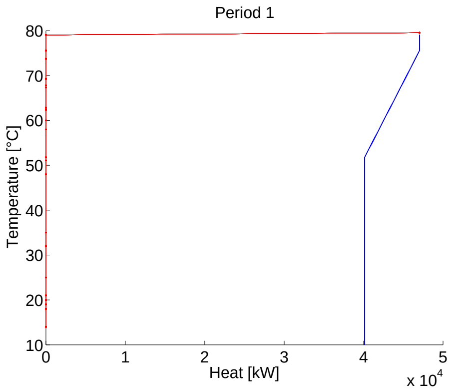


Composite curve of the winter day period

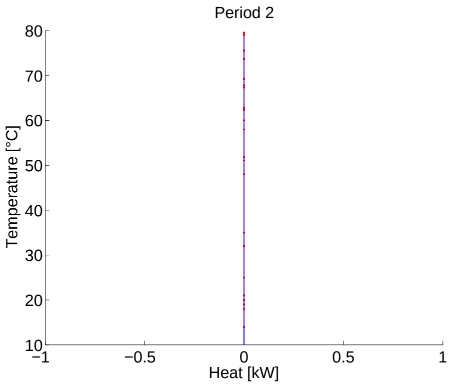


Composite curve of the winter night period

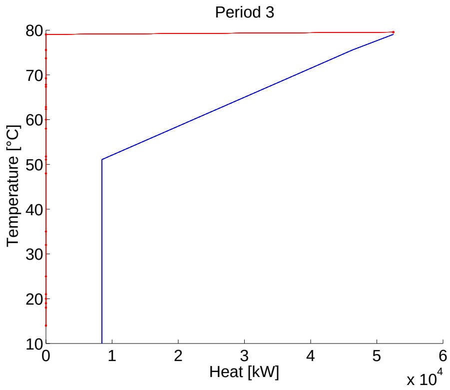
Figure 6.12: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration C1 (see Figure 6.9 and Table 6.6)



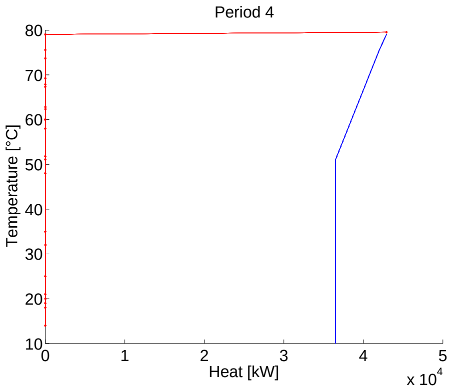
Composite curve of the summer day period



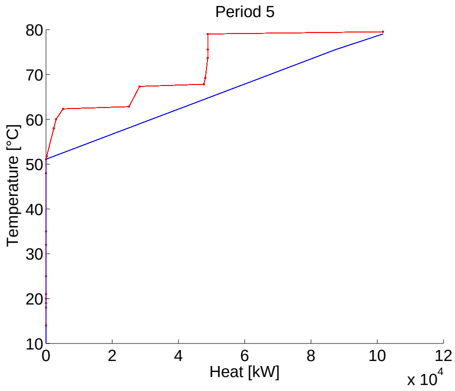
Composite curve of the summer night period



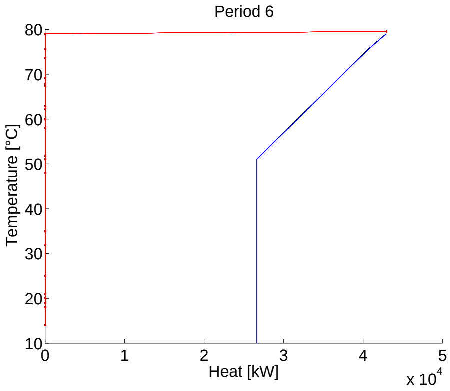
Composite curve of the mid-season day period



Composite curve of the mid-season night period

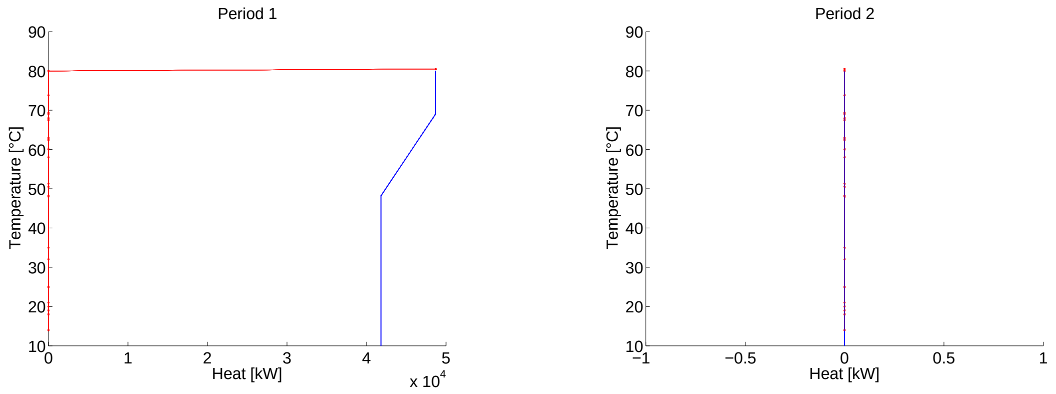


Composite curve of the winter day period



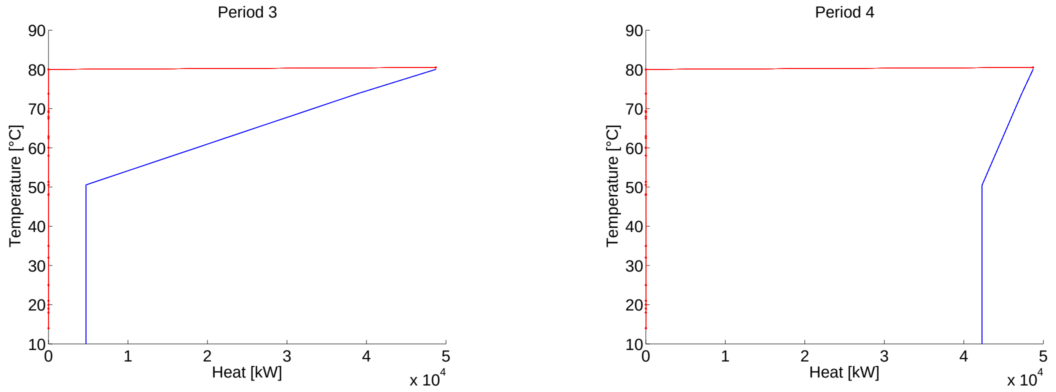
Composite curve of the winter night period

Figure 6.13: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration C2 (see Figure 6.9 and Table 6.6)



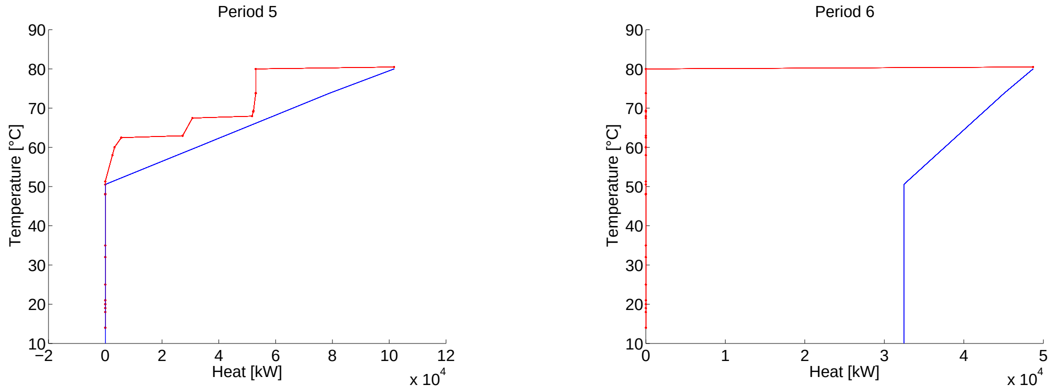
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

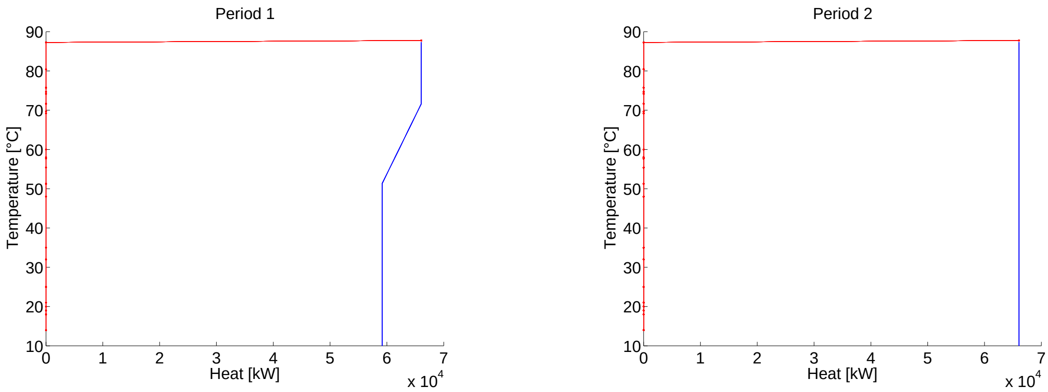
Composite curve of the mid-season night period



Composite curve of the winter day period

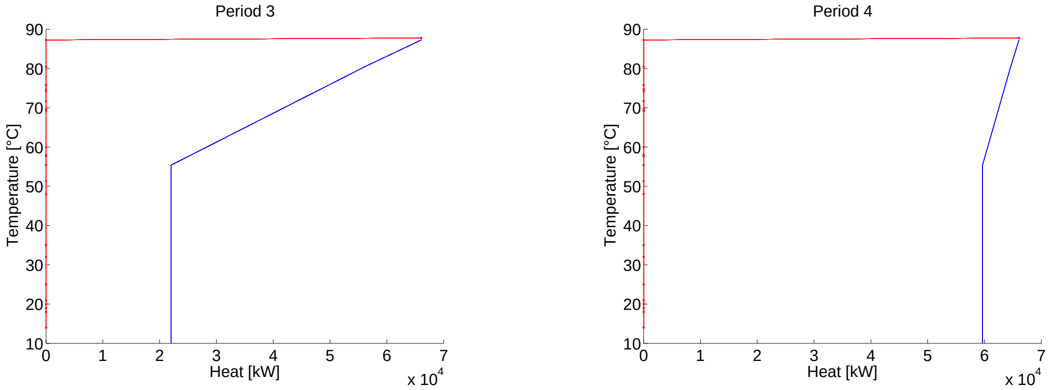
Composite curve of the winter night period

Figure 6.14: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration D1 (see Figure 6.9 and Table 6.6)



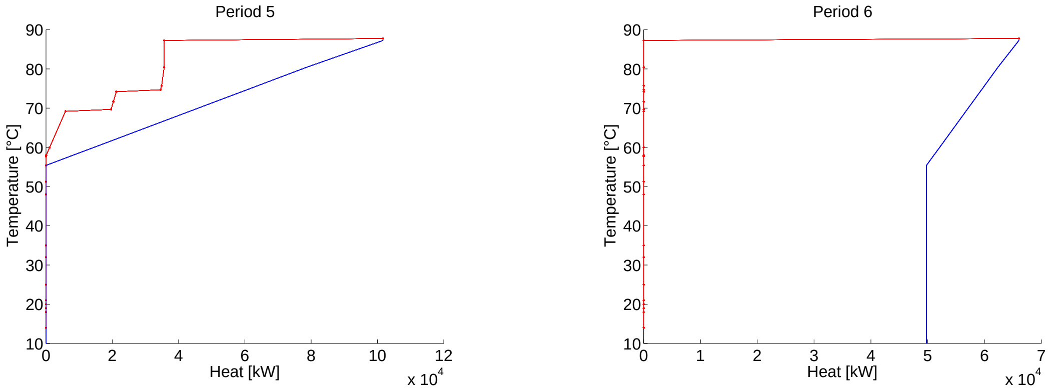
Composite curve of the summer day period

Composite curve of the summer night period



Composite curve of the mid-season day period

Composite curve of the mid-season night period



Composite curve of the winter day period

Composite curve of the winter night period

Figure 6.15: Composite curves for the heating and hot water requirements, as well as for the heating network, of configuration D2 (see Figure 6.9 and Table 6.6)

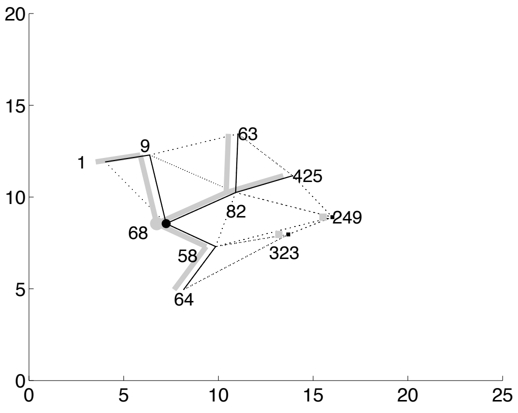


Figure 6.16: Cooling network (thin black line), heating and hot water network (large grey line) together with the individual back-up technologies for heating, hot water, and cooling (nodes 323 and 249), for configuration A1 (see Figure 6.9 and Table 6.6). The energy plant is located on node 68.

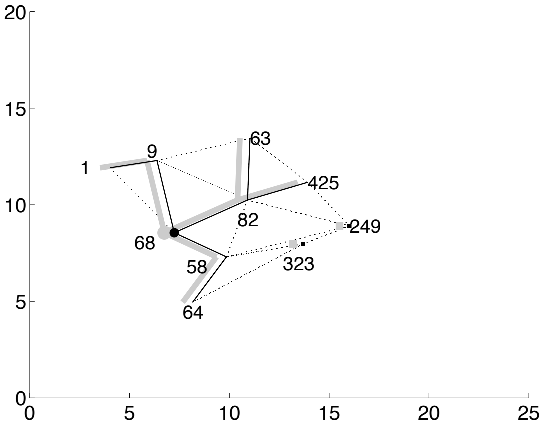


Figure 6.17: Cooling network (thin black line), heating and hot water network (large grey line) together with the individual back-up technologies for heating, hot water, and cooling (nodes 323 and 249), for configuration D2 (see Figure 6.9 and Table 6.6). The energy plant is located on node 68.

the heat losses and the investment costs for the pipes are dropped). Regarding the costs for the back-up individual energy conversion technologies implemented in sectors 249 and 323, following comment needs to be done: The cost parameters for the heat pumps have been approximated based on manufacturer data obtained for heat pumps ranging from 2 500 kWth to 20 000 kWth (see Table 6.4). However, sectors 249 and 323 require heat pumps that exceed 20 000 kWth, therefore the costs that have been computed for the required size but with the parameters given in Table 6.4 can only give an approximation of the total costs. Besides several heat pumps will most probably have to be implemented in parallel. Moreover, since the nodes in the sectors represent in fact sub-stations of a large district energy system and not the end-consumers (or buildings), a cost estimate for the distribution network from the sub-station to the end consumers should be accounted for when computing the annual costs of the district energy system. Such an estimate could be obtained by running the DESD(OP)^2 for each sector independently (knowing the results for the design of the overall district energy system of the first optimization run shown in the present chapter). Note however that adding the costs of the distribution network in each sector to the costs given in Figure 6.9 would only shift the Pareto optimal frontier up (in the direction of higher costs), but not change its shape. What distinguishes essentially the different clusters is the operating mode of the natural gas combined cycle. In cluster A, the combined cycle is operated at, or near, nominal load during the day periods, but shut off during all the night periods. This can be seen on the composite curves of Figure 6.10: no heat is delivered at the winter supply temperature level of the heating network, which would be the temperature level of the heat delivered by the combined cycle[3]. In cluster B, the combined cycle is operated during the winter night period (period 6), taking over the heat generation from the heat pumps, but remains shut off during the summer and mid-season night periods. This can again be seen on the composite curves of Figure 6.11. Besides, the HP2 type heat pump that was operated during periods 4, 5 and 6 in cluster A, only delivers heat during period 4 in cluster B. In the Pareto optimal configurations of cluster C, only one type of heat pumps is implemented, and it only delivers heat during the winter day period as shown on Figures 6.12 and 6.13(and is shut of during the rest of the year). The combination of both HP2 and HP3 heat pumps is not viable anymore (the part of the heat delivered by the combined cycle prevails and the increased costs accruing by the investment in two types of heat pumps cannot be offset by the improvement in the overall COP anymore). Finally cluster D follows behind cluster C, however with a weighting factor for the CO_2 emissions in the slave optimizer that is so small, that the slave optimizer can be considered as a pure single-objective optimizer having the costs as the one and only objective.

In all the clusters, as the emissions increase and the cost decreases, the size of the heat pumps decrease to count on favour of the size of the combined cycle. This can be seen in Table 6.6 when comparing configurations B1 and B2, C1 and C2, as well as D1 and D2. Besides, the electricity sold to the grid increases. In configuration D2, the cheapest configuration, the combined cycle is even operated during the summer night time (see Figure 6.15), in order to sell as much electricity as possible. However, even for this configuration, the district energy system cannot get off without buying any electricity from the grid, since the maximum total electricity requirements during the winter day period, including the district and decentralized heat pumps, exceeds the design size of the combined cycle. Since the same conditions have been applied as in Chapter 5 regarding the way to take into account the CO_2 emissions when electricity is sold to the grid[4], Figure 6.18 shows how the configurations of Table 6.6 change when the avoided CO_2 is considered.

6.4.4 Exergetic efficiency

A good performance indicator when comparing thermodynamic systems is the exergetic efficiency. It indicates how well an energetic system makes use of the distributed energy it gets as input, or, in other words, how big the losses of the energetic system are. The exergetic efficiency η of any system, is given in function of the exergy services received by the system $\dot{E}_{\text{in}}$, and delivered by the system $\dot{E}_{\text{out}}$:

$$\eta = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}} \tag{6.2}$$

To compute the exergetic efficiency of district energy systems, the following def-

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[3] Remember that the temperature in the condenser after the steam turbine in the combined cycle equals the supply temperature of the heating network in winter plus the minimum temperature difference of 2°C.

[4] The avoided CO_2 has not been accounted for.

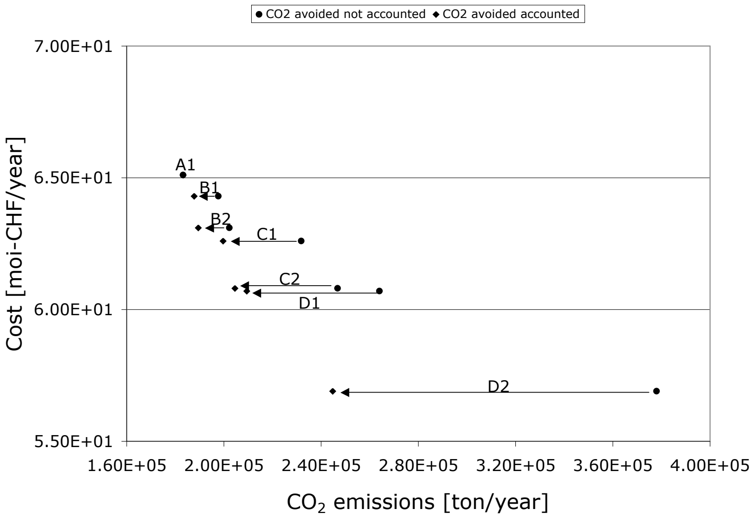

Figure 6.18: Influence on the annual CO_2 emissions of the configurations given in Table 6.6 when accounting for the avoided CO_2

initions/convention are adopted:

Energy system : Entire set of energy conversion technologies (district or individual), together with the distribution networks.

Exergy received by the energy system : Total of the distributed energies received by the energy system (natural gas, electricity from the grid and oil).

Exergy delivered by the energy system : Exergy required by the buildings for heating, hot water, cooling and electricity. Since the exergy delivered by the energy system corresponds to the exergy requirements of the buildings for the different services (heating, hot water, cooling and electricity), it is always the same for the district, regardless of the way this exergy is delivered (district or individual energy conversion technologies). One exception though concerns the electricity sold by the energy system to the grid, I^{el}, which can change according to the technologies implemented in the district. Therefore Table 6.8 gives the exergetic efficiencies with and without the electricity sold.

For the electricity requirements, the exergetic value has been set equal to the energetic value. For the thermal exergy services, the average hourly exergy rates have been computed using the general Equation 6.3 [38], in which $\dot{Ex}_{\mathrm{q}}$ is the exergy rate associated to the energy rate $\dot{Q}$. A constant temperature of $T = 23°\mathrm{C}$ for cooling (summer) and $T = 20°\mathrm{C}$ for heating (midseason and winter) is assumed in the buildings[5], as well as a temperature of $T = 60°\mathrm{C}$ for the hot water. The atmospheric temperatures considered are given in Table 6.2.

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[5] Because cooling requirements do occur during the summer night period, even though the atmospheric temperature is below the temperature level of these requirements, the exergetic value for the delivered cooling becomes negative. However, due to the relatively low cooling requirements

$$\dot{E}x_{\mathrm{q}} = \int \left(1 - \frac{T^{\mathrm{atm}}}{T}\right) \cdot \delta \dot{Q} \quad [\mathrm{kW}] \tag{6.3}$$

Table 6.7 shows for example the energy rates, and the corresponding exergetic rates for sector 425.

Energy/exergy service	Period	Energy rate kW	Exergy rate kW
Heating	Winter day	19 478	1 263
Hot water	Winter day	1 543	273
Cooling	Summer day	2 125	14
Electricity	Winter day	4 487	4 487

Table 6.7: Energy and exergy services for the winter day period, for sector 425

To compute the yearly exergetic efficiency of the district, the average hourly exergy rates for all the exergy services are integrated over the duration of each period, and summed up over all the periods and all the buildings, as shown in Equation 6.4 for heating. This summation results in a yearly exergy requirement in kJ/year for the whole district.

$$Ex_H = \sum_k \sum_t \dot{E}x_{H,t,k} \cdot D_t \quad [\mathrm{kJ}] \tag{6.4}$$

The exergetic efficiency is then given by the ratio of the total annual exergy requirements of the district and the exergetic value of the total distributed energies provided (electricity from the grid, natural gas and oil). The electricity *from the grid* is assumed to have an exergetic efficiency of 63.6%[6], resulting in an exergy input to the district of 1.57 kWh/kWh electricity. The exergetic value of the natural gas and the oil have been assumed equal to their respective energetic values.

The total exergy required by the district amounts to 293 GWh/year. The exergetic efficiency for configurations A1 and D2 of Table 6.6 are given in Table 6.8. The first column gives the exergetic efficiency including the electricity sold to the grid, and the second column the exergetic efficiency considering only what is directly consumed by the buildings in the district. Since no electricity is sold in configuration A1, both efficiencies are the same. The efficiencies given in Table 6.8 may seem high

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during the summer night period, compared to all the other energy services provided over the year, the yearly exergetic efficiency of the system is affected by a relative error of less than 5%.

[6] The exergetic efficiency of hydro electricity amounts to 88%, the exergetic efficiency of nuclear electricity to 32%, and the exergetic efficiency of waste incineration plants to 23% [38]. Considering that in Switzerland 57% of the total electricity is hydro, 39% nuclear, and 4% thermal (essentially waste incineration), the overall exergetic efficiency of the electricity from the grid can be approximated to 63.6%.

Configuration	η with I^{el}	η without I^{el}
"Initial"	25.3 %	25.3 %
A1	38.5 %	38.5 %
D2	44.0 %	17.9 %

Table 6.8: Exergetic efficiencies of configuration "Initial", A1 and D2 (see Table 6.6)

compared to values calculated elsewhere for Switzerland [38]. Favrat et al. indeed computed values ranging between 2.2% for the worst case (direct electric heating), up to 15.4% for the best case (district heat pump with hydro power). However, Favrat et al. considered only heating in their calculations, and didn't take into account electricity nor cooling (which is always given "for free" in the present case thank to cooling with water from the River Rhône). The best exergetic efficiency is found for configuration D2 if one takes into account all the electricity sold (which is a debatable assumption since it is not straight forward that the grid will always be able to buy the excess electricity generated by various district energy systems). Otherwise it's the solution featuring the least CO_2 emissions that also has the best exergetic efficiency. Without going into a detailed analysis of the exergy losses, the two following major sources of losses can nonetheless be mentioned:

1. In the slave optimization, which is an optimization based on costs, the configuration including a distribution network together with water/water heat pumps to locally increase the temperature level of the network, never comes out. The reason is that investing simultaneously for a distribution network *and* local water/water heat pumps never appeared to be interesting. Therefore, if a building is connected to the network for the heating requirements, it will also have its hot water requirements met by the heating network. In other words, the supply temperature of the network is governed by the required temperature level of the hot water requirements. This means that there are exergy losses occurring while meeting the heating requirements due to the temperature gap between the heating supply network and the requested temperature level of the heating requirements. To counter this issue, the slave optimization could optimize the exergetic efficiency instead of the costs.
2. As can be seen also on the composite curves (especially on Figure 6.15), large exergy losses occur when heat from the combined cycle is lost to the surroundings.

6.4.5 Price of electricity

Since the district energy system always sells electricity to the grid, and even makes it almost a priority in cluster D, where configuration D2 operates the combined cycle at nominal load during all the periods, an interesting figure to compute is the cost accruing when generating this electricity, and to compare this figure with the selling and buying price of electricity to/from the grid (0.09 CHF/kWh respectively 0.13 CHF/kWh). The cost accruing to generate the electricity is computed with the following equation, in which C^{CCGT} is the annualised investment cost of the combined cycle, C^{boiler} the annualised investment cost of the boiler that would be necessary to generate the requested heat if there was no combined cycle, C^{gas} the cost of the gas used by the combined cycle, C^{oil} the cost of the oil that would be used by the boiler (all the costs are in CHF/year), and finally E^{CCGT} the electricity generated in kWh/year :

$$c_{\text{el}} = \frac{(C^{\text{CCGT}} - C^{\text{boiler}}) + (C^{\text{gas}} - C^{\text{oil}})}{E^{\text{CCGT}}} \quad [\text{CHF/kWh}] \tag{6.5}$$

Table 6.9 shows the energy delivered by the heat pump and the combined cycle during each period (configuration D2), as well as the heat required by the sectors (except sectors 249 and 323 which are not connected). From this table, one can see that during the winter day period, the combined cycle can be considered to replace a 65 985 kWth large boiler ($65985 = 101733 - 35748$). Besides, since the heat pumps are not operated else than during the winter day period, this boiler would have to meet the heat requirements of all the other periods. Considering the duration for each period given in Table 6.2, and a boiler efficiency of 0.8, this would result in the oil consumption given in the last column of Table 6.9 for each period, and a total of 381 777 MWh/year. Table 6.10 gives the costing parameters (the interest rate for the boiler amounts to 0.08, the maintenance factor to 0.06 and the lifetime to 25 years). The price for the generation of electricity results in 0.06 CHF/kWh, which is lower than the selling price (0.09 CHF/kWh) and therefore encourages the energy system to sell as much electricity as possible.

Period	Average hourly energy delivered			Average hourly required heat rate	Oil for boiler
	CCGT	CCGT	HP3		
	Heat kWth	Electricity kWel	Heat kWth	kWth	MWh
1	66 055	99 052	0	6 904	9 449
2	66 055	99 052	0	0	0
3	66 055	99 052	0	44 016	120 493
4	66 055	99 052	0	6 411	139 246
5	66 055	99 052	35 748	101 733	90 317
6	66 055	99 052	0	16 272	22 272

Table 6.9: Heat and electricity delivered by the district technologies and required by the sectors

NGCC	mio-CHF/year	14.1
Boiler	mio-CHF/year	0.29
Gas NGCC	mio-CHF/year	64.3
Oil Boiler	mio-CHF/year	24.6
Electricity generated	MWhel	867695
Price of electricity	CHF/kWhel	0.06

Table 6.10: Cost parameters and resulting price for the production of electricity

6.5 Sensitivity analysis

In this section the results of the following two sensitivity analysis are shown: gas price and electricity mix.

6.5.1 Gas price

A sensitivity analysis has been performed on the price of the fossil fuels (natural gas and oil), assuming an increase of 10% on both the gas and oil prices given in Table 5.5. Figure 6.20 shows how the Pareto optimal frontier of Figure 6.9 is affected by the new prices. This new curve has been computed by increasing the operational costs related to the natural gas and the oil by 10%. The curve is basically shifted upwards, towards higher total annual costs. In cluster C, the new Pareto curve features an increasing trend between configurations c' and c", clearly demonstrating that choosing a configuration between c' and c" when the prices of the fossil fuels are low, ends up being inappropriate as soon as the prices of natural gas and oil increase. In cluster D, the trend between points d' and d" features a much flatter slope compared to the same configurations in Figure 6.9. This again demonstrates that choosing a configuration among the ones situated between configurations d' and d" ends up being a bad choice if the price of the fossil fuels increases too much[7]. The configurations given in Table 6.6 are shown explicitly on Figures 6.19 and 6.21 (the latter figure includes the avoided CO_2).

6.5.2 Electricity mix

The Pareto curve given in Figure 6.9 has been computed using the European mix for the CO_2 emissions related to the electricity from the grid (namely 0.45 kg/kg-CO_2). This hypothesis is justified by the fact that cogeneration units in Switzerland will

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[7] The sensitivity analysis has been made by increasing the price by 10% only. However, the way the slope between configurations c' and c", and between configurations d' and d", evolves, compared to the Pareto curve shown in Figure 6.9, indicate that when the prices increase by more than 10%, the slope between configurations d' and d" can also become ascending.

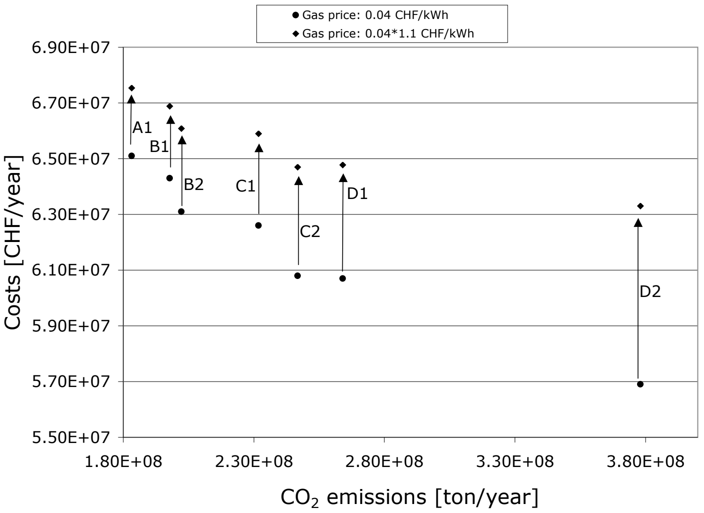

Figure 6.19: Influence of a 10% increase on the gas and oil prices given in Table 5.5, on the configurations of Table 6.6

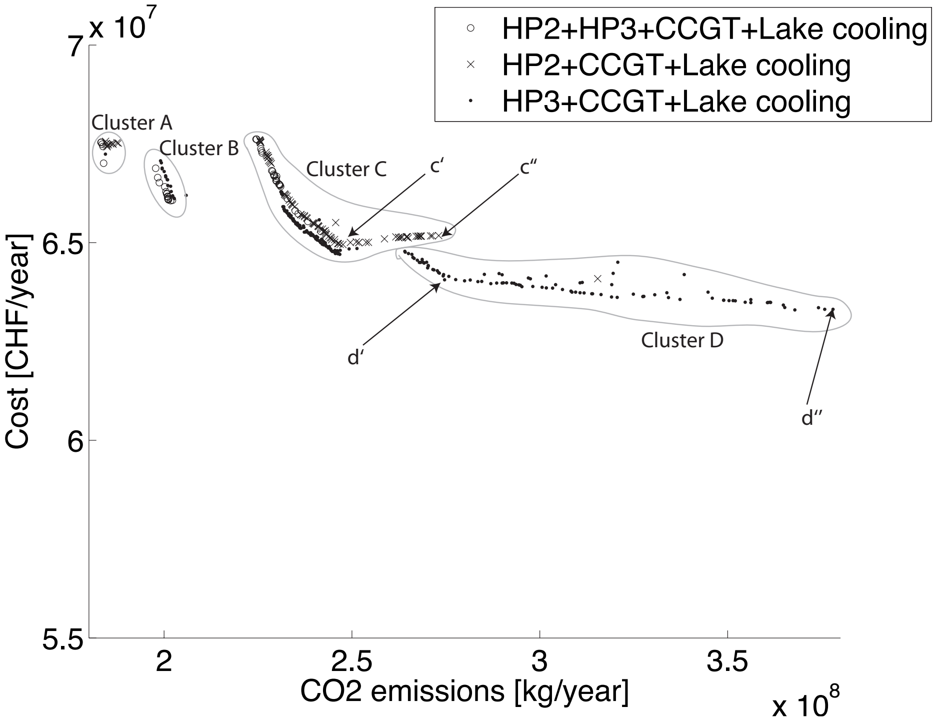

Figure 6.20: Pareto optimal frontier for the Geneva case study, computed with the cost parameters given in Tables 5.5 and 6.4, but with a 10% increase on the gas and oil prices

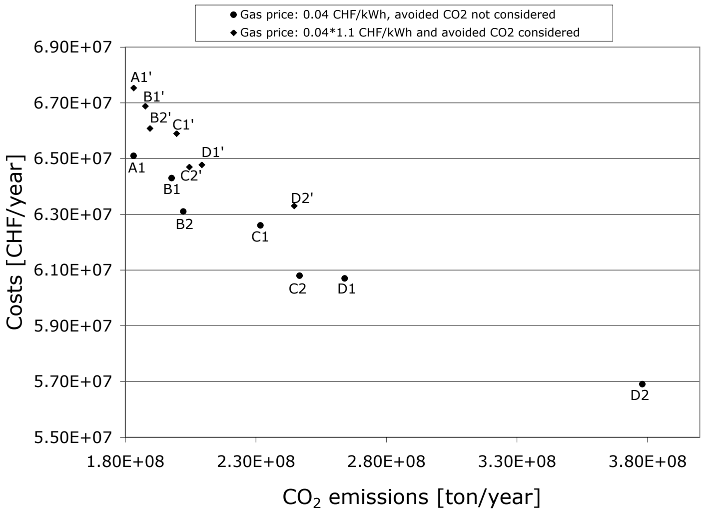

Figure 6.21: Influence of a 10% increase on the original gas and oil prices given in Table 5.5 *combined* with the avoided CO_2 on the configurations of Table 6.6 (the configurations marked with a ' , like A1' for instance, are the configurations including the price increase of 10% on the fossil fuels and the avoided CO_2)

rather replace the import of European electricity in winter. However, it appeared interesting to run an optimization using the Swiss mix, 0.110 kg-CO_2/kWhel [40], all other parameters remaining equal). This new curve is shown on Figure 6.22. The basic shape of the curve remains the same, and even when using the Swiss mix, cogeneration combined cycles coupled with heat pumps show to be interesting solutions. One can see that the least emitting configurations of Figure 6.9, which were the ones that bought more electricity from the grid, have logically been shifted to smaller values of CO_2 emissions. The new least emitting configuration emits 47 030 tons-CO_2/year versus 183 228 tons-CO_2/year with the European mix. On the other hand, the configurations with the higher electricity sales remain in the same range of CO_2 emission values since they are less affected by the change. As an example to compare with, a simulation of a configuration implementing *only* heat pumps for heating and hot water[8], *without* any combined cycle, and considering the Swiss mix, resulted in an emission value of 48 430 tons-CO_2/year for 74.6 mio-CHF/year. Unlike the Pareto curve of Figure 6.9, configurations implementing both HP2 *and* HP3 types heat pumps, can be found all along the curve shown in Figure 6.22.

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[8] The sizes of the heat pumps have been chosen so as to meet the requirements of the same nodes than in configuration A1, Table 6.6

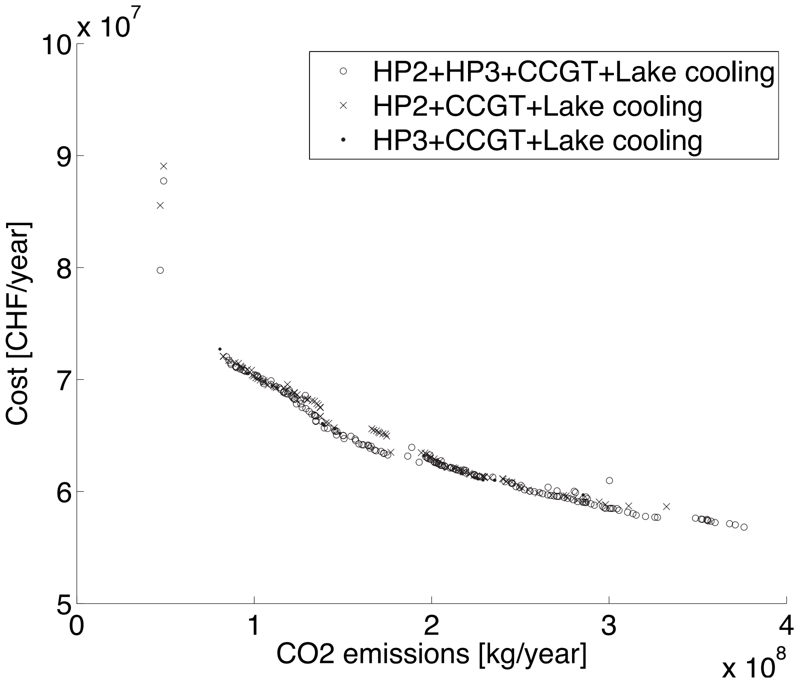

Figure 6.22: Pareto optimal frontier computed with the Swiss electricity mix

6.6 Conclusion

This chapter gives some inputs on the way the required information in the structuring phase can be obtained when no or little measurements are available, and which information sources can be of interest. Beside, this chapter demonstrates the ability of the DESD(OP)^2 method to handle not only districts with small to medium energy consumption levels like in the previous chapter, but also districts featuring large energy requirements and for which the goal is more to set the basis of a future energy system, than to design a network in all the details. The same method can thus be applied in different stages of the planning of a new district energy system: in a first round the method can be applied with aggregated information (aggregation of all the buildings in a sector for instance) and very simplified models. Once the situation in the district has been assessed, a second "round" can be run for the different sectors, imposing the energy services provided by the sub-stations, to compute the distribution network(s) in the sectors and optimize the operation strategy of the sub-stations according to the method developed in [99]. Moreover, this chapter demonstrates different interesting ways to analyse the results (exergetic efficiency, generation costs of electricity), that can be retaken in a post-processing phase to evaluate the different solutions (especially the exergetic efficiency for instance that has been taken up in the law on energy of the Canton of Geneva).

Chapter 7

CO_2 network

7.1 Introduction

This chapter departs from the subjects treated up to this point, namely the tool to solve the DESD(OP)^2 problem. It focuses on a new concept of district energy system that led to the submission of a patent, namely a CO_2 based district energy system (as opposed to the conventional water based systems treated so far). The driving forces that led to the development of a new system are first introduced, before going into a detailed description of the system. The chapter ends with a comparison between conventional water systems and the new CO_2 system, based on the test district that was generated to develop the method presented in this thesis.

7.2 Motivation for the development of a new system

To transfer the energy from the large polygeneration energy conversion technologies to the users, conventional district energy systems, like the ones which are the topic of the previous chapters, use water as energy transfer medium with often two independent supply and return piping systems for heating and cooling. However, sharing energy or interacting with decentralized heat pump units often results in relatively large heat transfer exergy losses due to the large temperature differences that are economically or practically (hot water) required from the water network (see Paragraph 6.4.4 for instance). Moreover, in *existing* district heating networks, the high temperatures often prevent from implementing heat pumps at the heating plant, or, if heat pumps can be used, then a relatively low COP results. Beside these thermodynamic considerations, additional practical and safety related issues emerged during the present thesis when it came to analyse the feasibility of a district energy system for an existing district downtown Geneva[1]. The main constraint

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[1] This district downtown Geneva shall not be mixed up with the district of Chapter 6

for the district energy system was that the pipes had to be implemented in already existing underground channels, like the one pictured in Figure 7.1. As can be seen from the picture, the channels are already densely packed with supports holding telecommunication and electric wires, so that not much space is left available. Besides, the space in the upper right corner is de facto not usable. For safety reasons it is not possible to put a water pipe above the wires, in case of leakage. Therefore, the only space that would really be available is a 40 mm by 60 mm section in the lower right corner (the two large pipes on the ground are the supply and return potable water), for a total of three or four pipes (return and supply heating and cooling pipes).

These different drawbacks led to the development of a new system, that can possibly alleviate issues such as high exergy losses, space problems and safety, using a refrigerant instead of water, as the energy transfer fluid.

7.3 Major advantages of CO_2

Configurations including a three pipe system, circulating a refrigerant to take advantage of the latent heat, have been analysed [36]. However the best fluid candidates analysed at the time, like HFCs or ammonia, present major feasibility drawbacks. Hence the choice of CO_2, as a natural, non toxic and non flammable fluid, is being considered for district energy networks. CO_2 as a refrigerant is gaining in importance at least for automotive air-conditioning and domestic water heating systems. Besides it can be envisaged both as the network fluid and as the working fluid for the heat pump units. In the CO_2 based district energy system presented, the driving force for the energy transfers is the phase change involving the latent heat of CO_2, thus helping to reduce the exergy losses. Moreover, due to its chemical properties, CO_2 is a good candidate when safety issues like the ones mentioned in Section 7.2 are relevant. One issue nonetheless remains with the use of CO_2. If in refrigeration units, CO_2 results in the same reversed Rankine cycle as common refrigerants, in heat pumping, supercritical cycles are to be used with a large glide instead of the plateau of condensation of most conventional refrigerants. This implies that CO_2 is well suited for large temperature glide applications like hot domestic water but less adapted to conventional heating networks, which have only a temperature glide of 5 to 15°C. Moreover CO_2 critical pressure is high (7.4 MPa) for a temperature of only 31°C (see Appendix A.5). In the following, a 2-pipe (a liquid and a vapour pipe) CO_2 network is explained, as well as the way it meets heating, hot water, air-conditioning and refrigeration requirements.

7.4 CO_2 district energy system

Considering that the cold composite curve of most buildings is rather flat with a low temperature glide of the heating heat exchanger, which is dominant in heat rate,

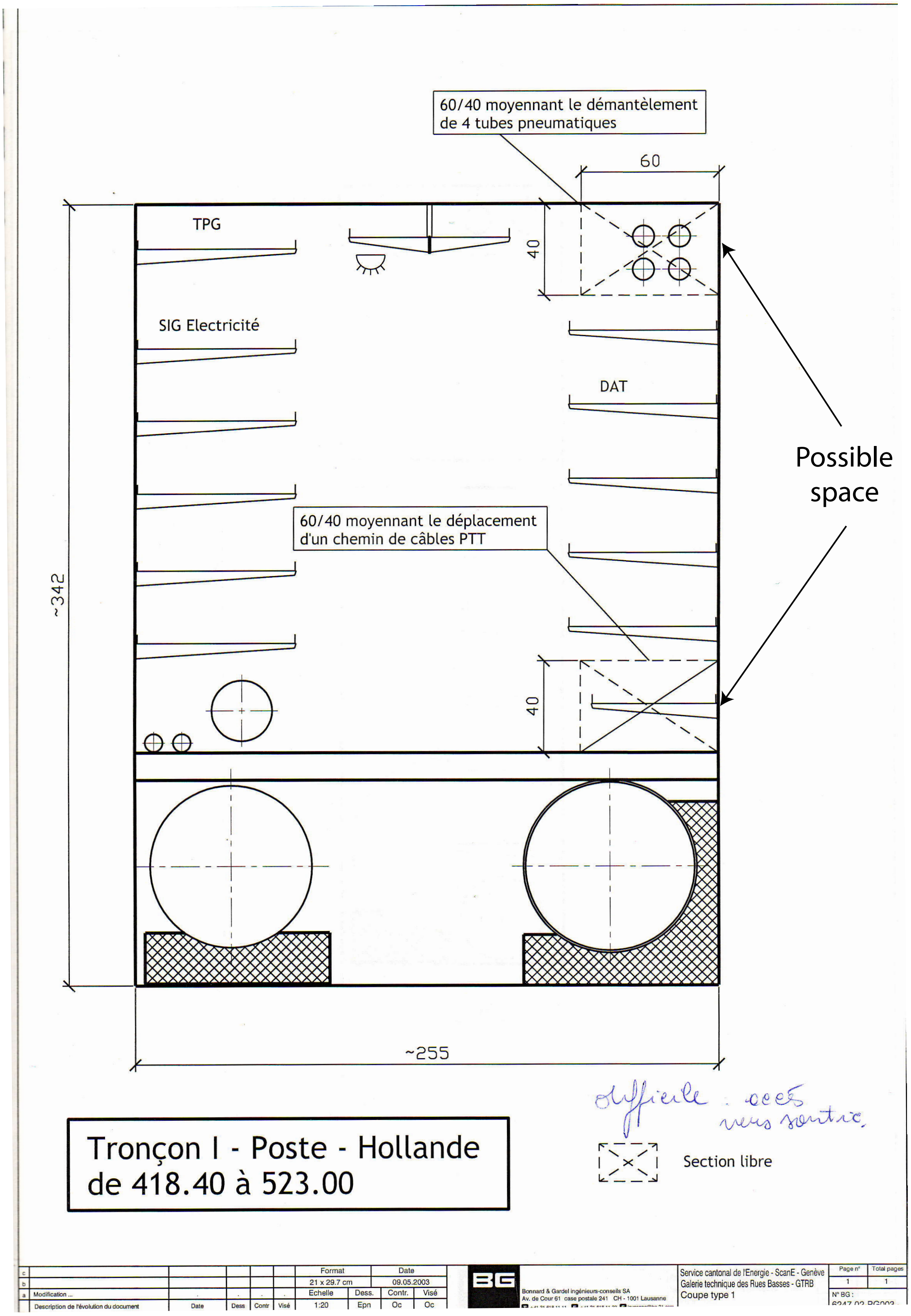

Figure 7.1: Underground channel in the analysed district downtown Geneva [9] (the dimensions on the picture are indicated in mm)

one concept is to distribute CO_2 in a district heating network at an intermediate temperature below the critical pressure. CO_2 then still presents a condensing plateau and can be a cold source for a decentralized heat pump working with a conventional refrigerant with zero glide, like HFC134a, or a small glide, like HFC-407C. In this case, the CO_2 condensing and HFC evaporating temperature profiles are similar, which allows a very small pinch and therefore small exergy losses. The advantage of such a solution is that the decentralized heat pump temperature lift can be tailored to the real heating needs of the building considered. For domestic water preparation, a decentralized dedicated CO_2 compressor can be directly used in an open cycle. The system can also take advantage of a small pressure difference between both pipes (the liquid pressure being higher than the gas pressure), to allow for air-conditioning without any powered equipment (pump or compressor). Such considerations guide the choice of the average pressure to be in the range of a saturation temperature of 18°C. Besides, in the event of having a high temperature heat source in its vicinity, the CO_2 system can be used as heat sink for an ORC.[2] Whenever a heat source or heat sink is available at some place on the network, CO_2 can be evaporated or condensed according to the needs of the whole network. It is also interesting to note that CO_2 has a very low viscosity, leading to potentially small pressure drops in the pipes [85]. Finally, one can imagine to extract CO_2 from the network to extinguish fires, or to inject some CO_2 into the network. Thank to this advantage, the system could be implemented in smaller areas such as production plants, small districts or university campuses for instance, but also in larger areas such as towns.

Based on the above, a superstructure of a network is proposed. Like any district energy system, the CO_2 system studied comprises a heating/cooling central plant, a distribution network and the connections from the network to the different users, or the different suppliers (in case of CO_2 evaporation or liquefaction). The superstructure of the system is represented in Figure 7.2 and the different possible modes explained hereunder.

7.4.1 Heating/cooling plant

The two pipes of the network consist of liquid CO_2 for the first pipe and vapour CO_2 for the second pipe. At the district heating/cooling plant the pipes are connected to a heat-exchanger working either as evaporator in heating mode (winter) or as condenser in cooling mode (summer). A set of valves at the central plant couple the evaporator with an expansion valve and a compressor in the heating mode, and the condenser with a pump in the cooling mode. When dealing with a district located near a lake, a river, or a wastewater treatment facility, the available water can serve as heat source (heating mode) or heat sink (cooling mode). However, any other heat source such as solar energy, geothermal energy, seasonal heat storage, waste incineration... could also be used, directly in the heating mode, or over an absorption chiller in the cooling mode. To compensate pressure losses in the pipes and avoid parasitic boiling, intermediate circulation pumps could be implemented along the

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[2] Organic Rankine Cycle

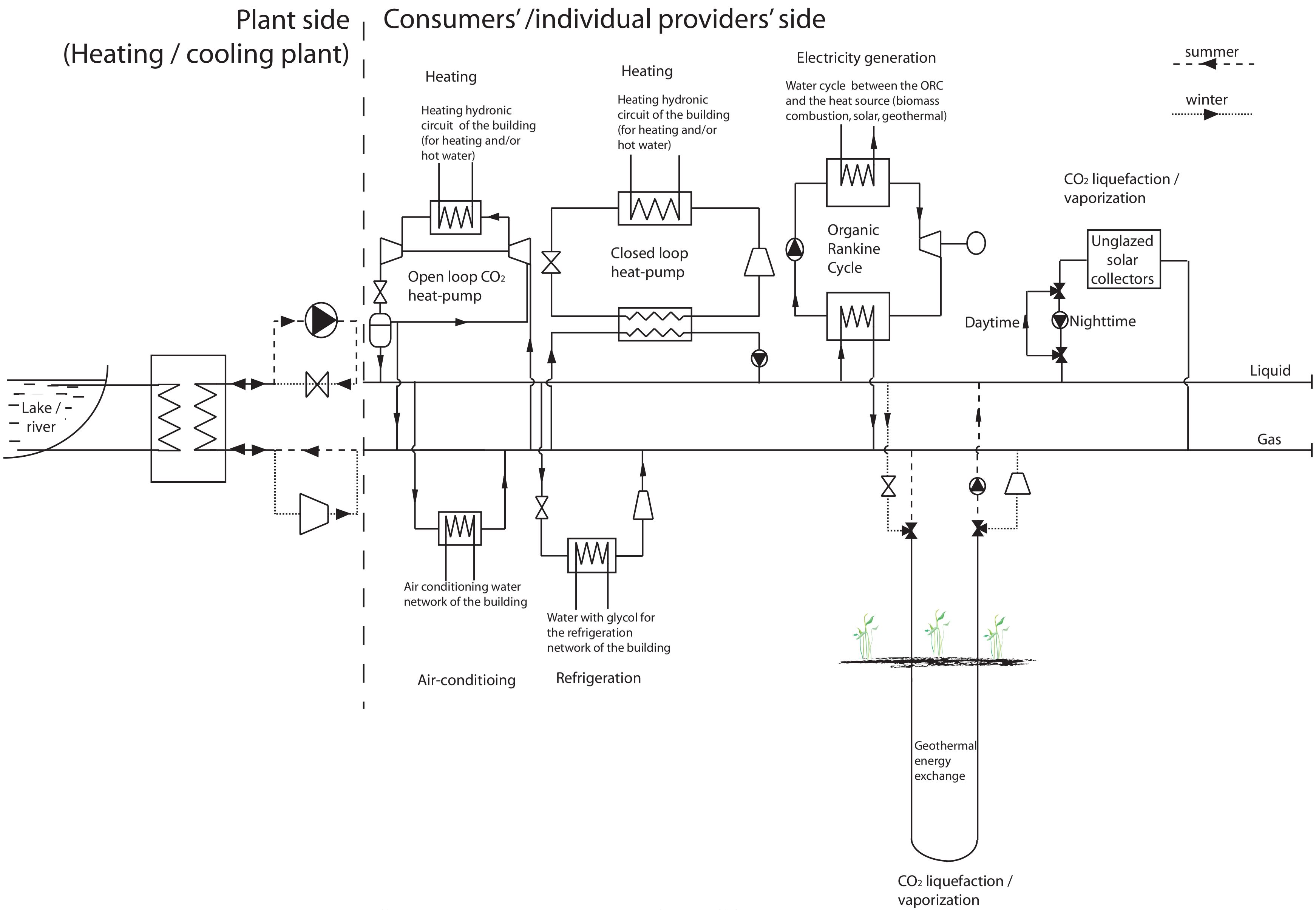


Figure 7.2: Schematic representation of the CO_2 based district energy system

network if requested. Unlike conventional district heating/cooling systems having dedicated supply and return pipes, with the system described here the direction of the flow in the pipes depends on the ratio of the heating (and/or hot water) and cooling (and/or freezing) requirements. If the total heating (and/or hot water) requirements in the district exceed the total cooling (and/or freezing) requirements, the vapour pipe is the supply pipe and the liquid pipe the return pipe. In this case, the CO_2 is evaporated at the central plant and pumped to the customers. On the other hand, if the total cooling (and/or freezing) requirements in the district exceed the total heating (and/or hot water) requirements, the liquid pipe becomes the supply pipe and the vapour pipe the return pipe. In this case, the CO_2 is condensed at the central plant before being pumped to the customers.

7.4.2 Energy conversion technologies at the user end

As already mentioned, at the user end, following processes can take place: heating, hot water preparation, air-conditioning and refrigeration. Besides, assuming that another heat source is available at some place along the network (heat from a chemical industry for instance), the CO_2 network can operate as a heat sink for an ORC. In case geothermal collectors are available or possible (under green areas for example), CO_2 vapour could be generated in winter by means of a heat pump, and CO_2 liquefaction could take place in summer, when the air-conditioning requirements are predominant. Finally, if unglazed solar roofs are installed, CO_2 could be circulated through the solar panels in winter for instance, if the sun is shining, in order to generate additional CO_2 vapour to meet the heating and hot water requirements. In summer, at night, CO_2 could be liquified if the atmospheric temperature is below 18°C. In order to compare this CO_2 system with the conventional district energy systems operating with water, the heating, hot water and cooling processes are explained hereunder (the "Liquid" and "Vapour" pipes in the figure always refer to the pipes connecting the user with the heating/cooling plant):

1. HEATING AND HOT WATER (OPEN LOOP CO_2 HEAT PUMP)
   In heating mode, the CO_2 vapour is compressed according to the specific needs (temperature level) of the building. It then passes through the heat-exchanger where it releases its energy to the building heating network, before being circulated through an expansion turbine (if any mechanical energy can be recovered), an expansion valve and a separator. The liquid phase is sent to the liquid CO_2 pipe. The vapour phase is directly recirculated to the compressor. If the heating requirements decrease, thus diminishing the needs for CO_2 in the vapour phase, the CO_2 vapour can be circulated directly from the separator back to the vapour CO_2 pipe. This mode is especially advantageous for hot water preparation.

2. HEATING AND HOT WATER WITH A CLOSED LOOP HEAT PUMP
   A conventional heat pump can be used as superposed cycle in particular when

the heating temperature glide is small and disadvantageous for a supercritical CO_2 cycle.

3. Air conditioning
   In the air conditioning mode, liquid CO_2 is circulated from the liquid pipe, via the heat-exchanger where it is evaporated with the heat coming from the building, to the vapour pipe. Due to the slight over-pressure in the liquid pipe compared to the vapour pipe, no pump is required in cooling mode.

4. Refrigeration
   In refrigeration mode, liquid CO_2 is circulated over an expansion valve to the heat-exchanger where it serves as heat-sink to the refrigeration network of the building (for industrial refrigeration for instance). The expansion valve can be regulated so as to meet the exact refrigeration temperature required by the building. After the heat-exchanger, the CO_2 is compressed and sent back to the vapour line.

5. Electricity generation
   If a heat source with a high enough temperature is available somewhere along the CO_2 network, the network can operate as a heat-sink for an ORC and thereby generate some electricity.

6. Geothermy
   In cities and districts with big green parks, geothermal probes can be dug into the soil. In winter, geothermal heat could be used to evaporate liquid CO_2 using a heat pump, and therefore help providing the required CO_2 for heating and hot water purposes. On the other hand, in summer, vapour CO_2 can be liquified (mainly in the night-time) in order to have enough liquid CO_2 for the air-conditioning during the day. Geothermal energy can also be gained by means of geothermal structures implemented in the foundations of large multi-storey car parks.

7. Unglazed solar collectors
   Unglazed solar collectors mounted on the roof of buildings can help generate vapour CO_2. During the night-time, especially in summer, if the atmospheric temperature is below 18°C, the existing heat-exchanger can be used to liquefy vapour CO_2 for the daytime air-conditioning.

8. Combination
   The operating modes described above can also be combined. For instance the heating and air-conditioning modes can be combined at the customer end (Figure 7.3). When both heating and air-conditioning are required in the same building, this system directly transfers the energy from the evaporator (air-conditioning) to the heat-exchanger (heating and/or hot water) or vice-versa via the CO_2. When one of the two energy requirements exceeds the other, the CO_2 that cannot be reused internally at the customer end is circulated via the heating/cooling plant. In heating mode, the CO_2 vapour is compressed

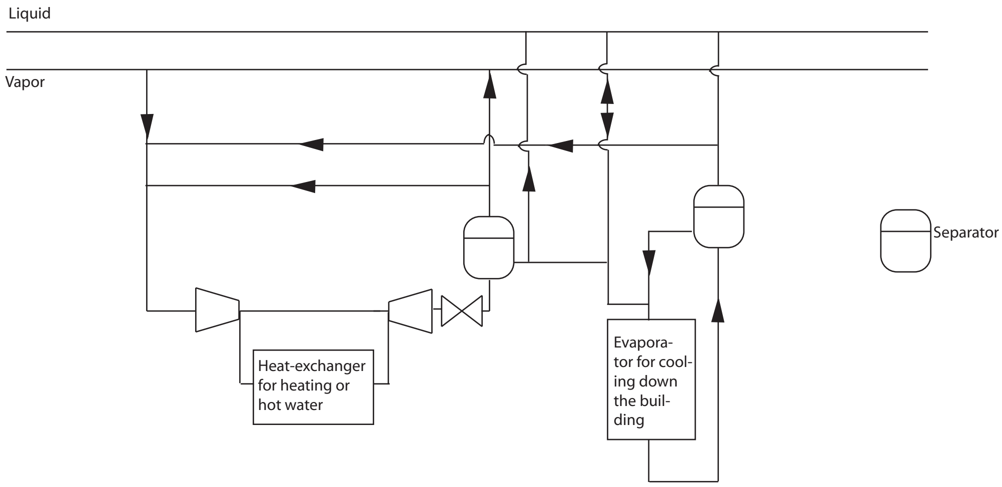


Figure 7.3: Combined heating and cooling mode

according to the specific needs (temperature level) of the building, as described above (Point 1). After having passed through the heat-exchanger, expansion turbine, expansion valve and separator, the liquid can be circulated directly to the evaporator together with any additional liquid CO_2 from the pipe of the network, if cooling is required in the building. The vapour on the other hand either flows back to the compressor, or, if the heating (and/or hot water) requirements decrease, to the vapour pipe. Likewise, the CO_2 evaporated in the evaporator (cooling mode) can be circulated to the compressor for heating (and/or hot water) requirements, via a separator to insure the vapour quality, or back to the vapour pipe.

9. CO_2 EXTRACTION OR INJECTION
   In case of CO_2 requirements (fire extinction) or generation (by-product of a process) along the network, the network could serve as CO_2-source or -sink.

From the description of the CO_2 based system it emerges that this system allows for a very efficient exchange of energy among the buildings connected to the network, and therefore to a very rational use of energy.

7.5 Comparison between the conventional water system and the new proposed CO_2 system

To compare conventional district energy systems with the CO_2 system, it is interesting to analyse how both systems perform in terms of annual costs and annual CO_2 emissions. For the costs, since the investment costs could not yet be evaluated for all the components (high pressure compressor for instance), the comparison focuses on

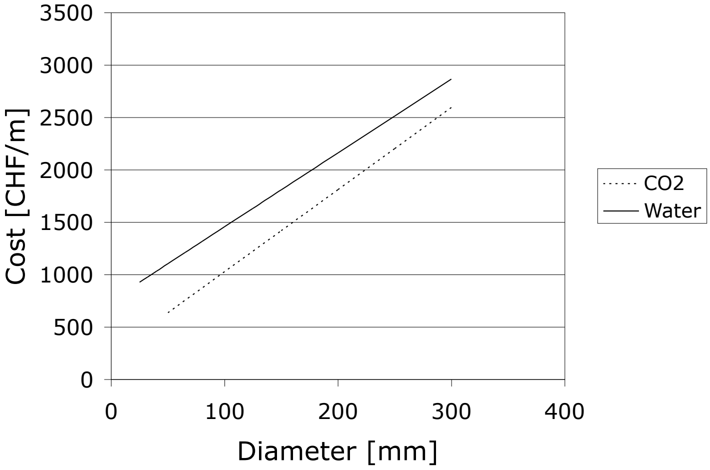


Figure 7.4: Costs of pressurized CO_2 pipes and water pipes (supply and return)

the investment costs of the pipes (which still act as a major brake upon investment in district energy systems) and on operation costs. Besides, since the space available for the pipes can be an issue at some places, dimensional aspects are also of interest. Figure 7.4 shows the costs in CHF/m for pressurized CO_2 pipes and for water pipes, for a set of supply and return pipes ([77] and [94]). The fact that the costs for pressurized CO_2 pipes are lower than the costs for water pipes might be a consequence of both costs having been obtained by different sources and shall not be further analysed. What is more interesting, and which has been confirmed by the suppliers, is that the order of magnitude for pressurized CO_2 pipes is the same as for water pipes [94].

To make the comparison, a district energy system implementing a CO_2 based network has been computed for the test district shown in Figure 5.1 and the related consumption profiles given in Figures 5.3 to 5.6. The CO_2 network includes (connects) all the buildings in the district. It is then compared with configuration 1A1 of Chapter 5. Since no heat source is available in the test district that could generate electricity by means of an organic Rankine cycle, all the electricity for the test case implementing the CO_2 network is taken from the grid. Because of the nature of the CO_2 based system, it is not trivial to attribute the operation costs to the different energy services. Cooling for instance only requires liquid CO_2 to flow through a valve and be evaporated, which by itself does not cost anything. However, cooling cannot be provided if there is not enough liquid CO_2, which is ensured either by the central heat pump or by the heating requirements of other buildings. Because of the energy exchange that takes place between the consumers over the CO_2 network, a consumer is automatically also a provider. Therefore, to compare both conventional and CO_2 based systems, the operation costs are not split up according to the different energy services but given for the system as a whole. The results are shown in Table 7.5. To compute the electricity consumption of the CO_2 based district energy system, the following assumptions were made:

1. For the heating and hot water requirements, closed loop heat pumps are implemented at the consumers' place.
2. To compute the COP of the closed loop heat pumps, the following temperatures/parameters are considered:
    - $T^{\text{cond}} = T_{Hs,t,k} + \Delta T = 62°\text{C}$ ($T_{Hs,t,k} = 60°\text{C}$, based on the temperature level of the hot water requirements which is assumed constant over all t and k)
    - $T^{\text{evap}} = 18 - \Delta T = 16°\text{C}$ (18°C being the temperature of the CO_2)
    - The exergetic efficiency amounts to 0.34 [47].
3. The efficiency of the compressor at the plant amounts to 90%.
4. The efficiency of the pump amounts to 80%.

It is difficult to make a reasonable comparison between both systems in terms of exergetic efficiency, since in one case the way electricity is generated is known, at least partly (configuration 1A1 implementing a gas engine), whereas for the other case it isn't (similar problem as in Paragraph 5.4.1). However, considering the same assumptions as in Paragraph 6.4.4, namely that the exergetic efficiency of the electricity from the grid amounts to 63.6%, and that the total required exergy amounts to 4.8 GWh/year (4 790 917 kWh/year) for the test district, and considering the values given in Table 7.1, the exergetic efficiency of the CO_2 based district energy system amounts to 29.6% (4.8/(10.3/0.636)=0.295). This efficiency is lower than the exergetic efficiency of configuration 1A1 (34.2%). However, like in Paragraph 5.4.1, the CO_2 system requires less distributed energy (like the two-pipe water system), and the way the electricity from the grid is generated will play a role. Besides, this example only takes into account part of the merit of the CO_2 system, since no heat recovery in the organic Rankine cycle, geothermal energy exchange or else CO_2 liquefaction or vaporization have been considered.

Figure 7.5 illustrates the space required for the pipes in the conventional water based system and in the new CO_2 based system. The figure shows the part of the network directly around building 5 in which the energy conversion technologies are implemented. From this figure it is obvious that the CO_2 network requires less space (the pipes have been drawn according to scale and can therefore be directly compared).

Parameter	CO_2 network	H_2O network Configuration 1A1
Annual investment costs for pipes [CHF/year]	94 747	192 121
Operational costs [mio-CHF/year]	1.34	0.70
Electricity purchased from the grid [GWh]	10.3	2.1
Natural gas [GWh]	0	10.6

Table 7.1: Comparison between a CO_2 based district energy system and a conventional water based system

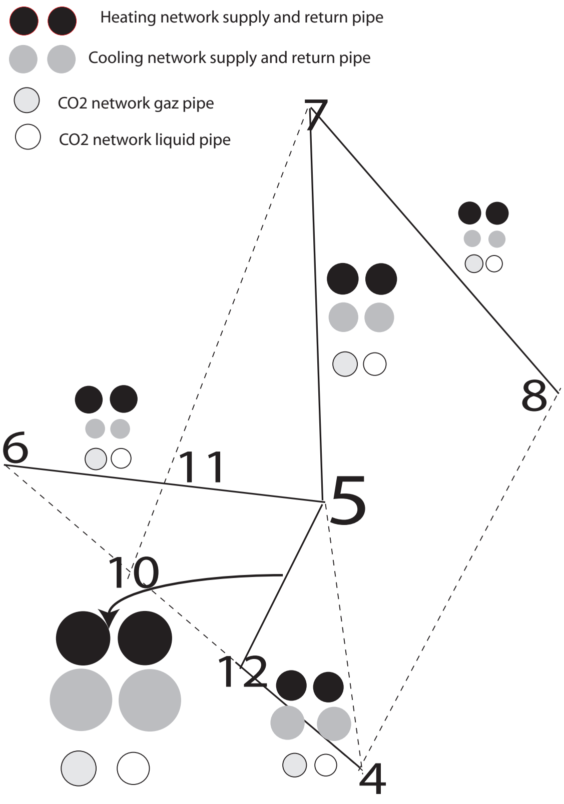


Figure 7.5: Space required by the pipes for a conventional water network and a CO_2 network

7.6 Conclusion

A new CO_2 district energy system is presented and compared with conventional water systems. The system heavily relies on decentralized heat pump and refrigeration units. This new system allows for a very efficient energy exchanges between the buildings connected to the network, and therefore allows for a very rational use of energy. It is further shown that piping can be reduced at least by half in terms of costs compared to an equivalent 4-pipe water system, due the fact that the CO_2 system only required two pipes.

Chapter 8

Conclusion and future work

8.1 Conclusion

The thesis starts demonstrating the need for a new tool to design and optimize district energy systems, including polygeneration energy conversion technologies as well as the distribution network(s). If polygeneration energy conversion technologies shall indeed play a major role in the future to mitigate CO_2 emissions linked with the satisfaction of the different energy services, no tool exists that gives an answer to the following questions: Given a district with its buildings and energy consumption profiles,

1. which type of polygeneration energy conversion technologies are best suited for the district?
2. where in the district shall these technologies be implemented (geographically)?
3. is it viable to combine these technologies with other technologies (like heat pumps)?
4. what are the optimal supply and return temperatures of the distribution networks (heating and cooling), considering the requirements of the district and the technical limitations of the technologies?
5. how shall the buildings be connected?

The main contribution of the present thesis, lies in the development of a method, that starts by analysing the information available in the Geographical Information Systems of the considered district, and, based on this, provides answers to these questions. The method developed integrates the following aspects:

1. Thermodynamic aspect: joint consideration of the different energy services, allowing for the implementation of efficient polygeneration energy conversion technologies, as well as in the consideration of the *temperature levels* at which the thermal energy requirements have to be satisfied, thus allowing for an optimal process integration.
2. Mathematical aspect: combination of different types of optimization algorithms, implementing each algorithm to optimize the variables it is best suited

for. The optimization phase is therefore divided in a master and a slave optimization, following mathematical and hierarchical decomposition strategies.

3. Conceptual aspect: Integration of time and space related constraints in a same problem.
4. Modularity: Possibility of designing energy systems for very different types of districts (different location, levels of requirements, building types,...) including very different types of technologies.

An important output of the method to help answering the questions mentioned above is the Pareto optimal frontier (Figures 5.7 and 6.9), showing the trade-offs between the CO_2 emissions and the costs for different configurations applying to the analysed district. The analysis of the configurations demonstrate the various capabilities of the method, such as, for instance:

1. the exclusion of nodes (buildings) from the distribution network,
2. the consideration of space limitations,
3. the optimal location of the energy plant, near the energy sources,
4. the definition of an operation strategy for the district as well as the individual back-up technologies.

Besides demonstrating the applicability of the method, the results further point out the importance of using heat pumps and of having an optimally integrated energy system, both in terms of CO_2 emissions *and* costs. In the Geneva case, the combined implementation of a combined cycle with heat pumps allows to reduce the CO_2 emissions by 45% with a parallel cost decrease of 24%. Finally, the method illustrates particularly well the sensitivity to the relative energy costs. As shown in Figure 6.20, compared to Figure 6.9, the favourable economic conditions of the solutions emitting more CO_2, when the relative price of gas to electricity is low, significantly decrease, when the relative price of gas to electricity increases. This reinforces the role of district heating heat pumps in the future.

The thesis also includes the description of a novel type of district energy system, the CO_2 based district energy system. The advantage of using a refrigerant such as CO_2, in the range of temperature considered (between 12 and 18°C of saturation temperature), is the significant latent heat. This latent heat implies that the CO_2 can in particular be used as a bottoming source for heating heat pump and as a cooling source for air-conditioning and/or refrigeration. The major interests of this system lie in the minimization of both the energy and exergy losses, with a maximization of the potential exchanges of energy between users. In addition to the more rational use of energy that such networks imply, additional synergies with fire extinguishing equipment or even later CO_2 collection and transport form fuel cell decentralized cogeneration units can be imagined. Moreover, it allows new alternatives in areas where underground space channel is limited, and/or water is not welcome like at the proximity of underground electric lines.

8.2 Future work

The development and application of the tool brought to the fore the following aspects, for which the tool cannot yet provide any answer and that require further development:

1. In Paragraph 5.4.1 it was shown by simple simulations that a two pipe cold water based system can be an interesting option in some cases, even for heating and hot water. The extension of the DESD(OP)^2 method to two pipes system is one of the most important issues that still has to be solved.
2. No real energy exchange takes place between the customers that require heat and the customers that require cooling (the heat pump that connects the return pipe of the cooling network with the supply pipe of the heating network is never implemented due to the bad match between the heating and cooling requirements). This issue has only been considered in the concept of the CO_2 based district energy system.
3. On the data level, the application of the method to real cases (be it the Geneva case presented in Chapter 6 or another case, in Martigny/Switzerland, published in [17]), demonstrated that many data were still missing and needed to be processed in order for the method to be applied. The development and/or improvement of Geographical Information Systems therefore remains an important issue.

Besides these three points, future work can be done on a methodological and a thermodynamic level:

METHODOLOGICAL LEVEL

1. The superstructure at each node should be enriched in order to allow for individual heat pumps that provide energy for heating and hot water purposes, to be connected to the cooling network. At present, individual back-up water/water heat pumps can only be used to increase the temperature level of the heating supply network. However, by adding this new type of heat pumps to the superstructures at each node, the cooling network used in summer for cooling purposes could be used in winter for heating purposes. This would avoid to have a heating and a cooling network running in parallel as shown on the various figures of Chapters 5 and 6. Appendix A.6 gives some hints on how this could be done.
2. The method should be adapted in order to deal also with the CO_2 network, and not only with water based networks. The major issue here would be the modelling of the different components, especially the compressor at the plant, that are exposed to very high pressures. Regarding the slave optimization, no big modifications are needed since the water, and therefore the energy flows, can flow either way in the pipes (no direction is imposed a priori, before starting the optimization). See also Appendix A.6.

3. If the DESD(OP)^2 tool can easily exclude from the distribution network(s) nodes that are located too far away from the other nodes in the district or that feature too small requirements, it is not strictly spoken the goal of the DESD(OP)^2 tool to make a first evaluation regarding the viability or not of a district energy system in a broader region (for instance the whole Canton of Vaud in Switzerland: 3 212 km^2 and 281 municipalities). The development of a tool that would come on top of the DESD(OP)^2 tool and evaluate the pertinence of a district energy system in a region before applying the DESD(OP)^2 tool, would be of great interest.

Thermodynamic level

1. Process integration: The method developed analyses two types of heat cascades (district technologies → network and network → consumers). It does this for the heating network and for the cooling network. However, the next step to a more integrated system is to consider also the heat cascades of the consumers themselves. Let us assume for instance that a consumer needs both heating and cooling *simultaneously*. At present, this consumer gets heat from the heating network and cooling from the cooling network. The valorization of the energy taken from the building while cooling it down, can only be done at the plant, with a HP1 type heat pump. However, circulating the energy from the building to the plant, and from the plant back again to the building, results compulsorily in energy losses that could be avoided.
2. Storage: No storage devices have been considered. However, storage devices allow a smoother operation of the energy conversion technologies by providing the excess energy required at peak loads, and storing the excess energy generated by the energy conversion technologies when the requirements in the district are at lowest [99].
3. Increase the choice of possible energy conversion technologies: Regarding district energy conversion technologies, that are modelled on the level of the master optimization, any technology can be considered since that part of the problem is not restricted to be linear. Regarding the individual back-up energy conversion technologies, any technology can be considered as long as its performances can be approximated with linear correlations. Even hybrid technologies such as fuel cells combined with micro-turbines could be considered, either by assuming that the hybrid technology is in fact *one* technology with given heat and electricity outputs, or by considering both technologies as two entities and adding constraints stating that if a fuel cell is implemented at some place, then it must be in conjunction with a turbine.

Appendix A

Appendix

A.1 Inconsistencies and unreasonable values

The reason for this can be illustrated by the following example. Let's assume that the slave optimizer is given the choice of a gas engine *and* a gas turbine by the master optimizer, both generating an amount of heat in the size range of the maximum total heating and hot water requirements. This will not lead to a better final solution than if the slave optimizer was given the choice of a gas engine *or* a gas turbine of the same size. There is indeed no situation for which it could be better to have two gas driven devices running in parallel at lower part loads, than to have only one device but running at a higher part load. It is therefore useless to simply pass both technologies to the slave optimizer, thus resulting in a too large search space for the slave optimizer and therefore a too large resolution time. However, the master optimizer must have the freedom to choose both gas driven devices in the whole size range available for the technology in order to have the choice of selecting only a large gas engine, only a large gas turbine, or one mid-sized gas engine and one mid-sized gas turbine together. Therefore, the issue here is that if the master optimizer chooses the maximum size for both gas driven devices in the *same* iteration, the data processing routine has to interfere and forbid that the total design sizes of all the technologies exceed the maximum thermal requirements by the value of the arbitrary factor. It does this by scaling down the sizes of the district technologies.

A.2 Upper and lower bounds

Let's assume that the binary variable related to the connection between two nodes is activated (= 1) if water is flowing between the two nodes. Theoretically, this can be formulated as follows:

$$X_{i,j} \cdot \boldsymbol{M} \geq \dot{M}_{t,i,j} \tag{A.1}$$

with $X_{i,j}$ the variable defining the existence or not of a connection between nodes i and j, $\boldsymbol{M}$ an arbitrarily chosen big value, and $\dot{M}_{t,i,j}$ the mass flow rate of water flowing from i to j during period t. If $\dot{M}_{t,i,j} > 0$, $X_{i,j}$ is activated. However, with such a constraint, the branch-and-bound algorithm can get difficulty in computing the optimal solution. Let's assume a sub-problem in the tree of the branch-and-bound algorithm for which $X_{i,j}$ is relaxed and $= 0.0001$ while the parameter $\boldsymbol{M}$ was given the value 999999999 at the beginning of the optimization. The equation above is verified as long as : $\dot{M}_{t,i,j} \leq 999999.999$. However, if $\boldsymbol{M}$ is chosen orders of magnitude larger than $\dot{M}_{t,i,j}$, the algorithm will lack information to be able to decide whether to round $X_{i,j} = 0.0001$ to 0 or to 1. In such a case, the algorithm will either not be able to compute the optimal solution because of unscaled infeasibilities, or find the optimal solution after having solved a much higher number of sub-problems of the branch-and-bound tree than would have been necessary if the constraint was more accurately formulated. A better formulation for the constraint above, leading to an improvement of the resolution time, is therefore to add a second constraint to the first one and to tighten the bounds:

$$X_{i,j} \cdot \dot{M}^{\mathrm{ub}} \geq \dot{M}_{t,i,j} \tag{A.2}$$

$$X_{i,j} \cdot \dot{M}^{\mathrm{lb}} \leq \dot{M}_{t,i,j} \tag{A.3}$$

with $\dot{M}^{\mathrm{ub}}$ and $\dot{M}^{\mathrm{lb}}$ the maximum and minimum (greater than 0) mass flow rates than can potentially flow in a pipe between two nodes of the district, all periods included. $\dot{M}^{\mathrm{ub}}$ and $\dot{M}^{\mathrm{lb}}$ can be easily computed by the data processor since the energy consumption profiles are known for the analysed district, and the supply and return temperatures of the network are given by the master optimizer.

A.3 Difference between clusters 1 and 2 of the test case

The small difference in costs between clusters 2 and 3 of the test case can be explained in more details as follows:

1. Depending on the values given by the master optimizer for the decision variables, the difference in the COP of heat pump HP2 and heat pump HP3 lies below 5%. Let's admit for instance following cases:

    (a) Heat pump 2, taking energy from the lake, and featuring an evaporator temperature in winter of 2°C: $T_{evap} = T_{lake} - \Delta T_{lake} - \Delta T_{evap} = 6-2-2 = 2$°C ($T_{lake}$ being the temperature of the lake, ΔT_{lake} the temperature difference between the inlet and the outlet of the evaporator for the water from the lake, and ΔT_{evap} the pinch in the evaporator), and a condenser temperature of 70°C. This results in a theoretical COP of 5.0.

(b) Heat pump 3, taking energy from the wastewater treatment facility and therefore being split in two heat pumps implemented in series (due to the high temperature difference that can be achieved with the wastewater), and featuring following evaporator temperatures

Heat pump 3a: $T_{evap} = T_{waste} - \Delta T_{waste} - \Delta T_{evap} = 16 - 5 - 2 =$ 9°C
Heat pump 3b: $T_{evap} = T_{waste} - \frac{\Delta T_{waste}}{2} - \Delta T_{evap} = 11 - 5 - 2 =$ 4°C
(T_{waste} being the temperature of the wastewater treatment facility, ΔT_{waste} the temperature difference between the inlet and the outlet of the evaporator for the wastewater, and ΔT_{evap} the pinch in the evaporator).

For the same condenser temperature as heat pump 2, namely 70°C, following theoretical COPs are achieved:

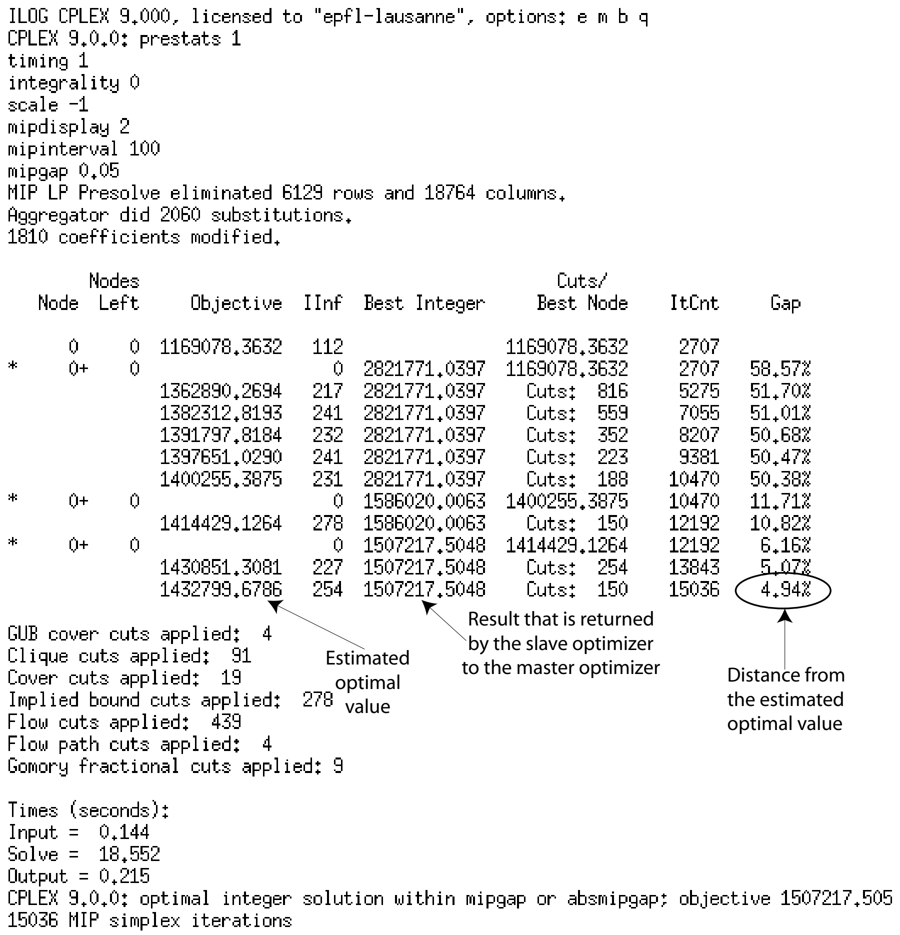
Heat pump 3a: 5.2
Heat pump 3b: 5.3

As expected, the COP of heat pump 2 is lower than those of heat pumps 3a and 3b. However, the difference is less than 5%, which in combination with following point 2, can finally result in an output of the master optimization featuring better objective function values when implementing heat pump 2 than heat pumps 3a and 3b.

2. The slave optimization returns its result to the master optimization as soon as it has found a solution that lies within 5% of what is estimated to be the optimal value (of the slave optimization). The estimation of the optimal value is based on some heuristics. As shown in figure A.1, the slave optimizer iterates until it has found the first feasible solution with an objective value within 5% of the optimal solution. However, the improvement of the value of the objective function is not linear. The improvement is small for instance between iterations 9381 and 10470 (50.47% to 50.38%), as compared to the improvement obtained between the first time iteration 10470 is calculated and the second time[1]. In the same way, the improvement between a configuration featuring a value for the objective function above 5% of the optimal value, and a configuration within 5%, can result in some cases in a result at 4.94% from the optimal solution for instance (like on figure A.1), and in other cases at 0.5%. Let's assume that for a configuration implementing a heat pump of type 2, the slave optimization returns a value within 0.5% of the optimal

---

[1] On figure A.1 *ItCnt* counts the numbers of the Simplex iterations done. However, beside using the Simplex algorithm to compute the optimal solution at each node in the tree (as explained in section 3.4), the Cplex solver can also apply heuristics to the fractional solutions computed, in order to find an integer solution. For instance in the case here, Cplex has found a feasible solution for the Simplex iteration 10470 that resulted in a value for the objective function at 50.38% from the estimated optimal value. However this solution is fractional (in other words, the integer variables do not all have integer values). By applying some heuristics on this result but *without* making a new Simplex iteration, Cplex was able to find a feasible *integer* solution at 11.71% of the optimal solution.



```
ILOG CPLEX 9.000, licensed to "epfl-lausanne", options: e m b q
CPLEX 9.0.0: prestats 1
timing 1
integrality 0
scale -1
mipdisplay 2
mipinterval 100
mipgap 0.05
MIP LP Presolve eliminated 6129 rows and 18764 columns.
Aggregator did 2060 substitutions.
1810 coefficients modified.

        Nodes                                              Cuts/
    Node  Left     Objective  IInf  Best Integer     Best Node    ItCnt     Gap

       0     0  1169078.3632   112                1169078.3632     2707
*     0+     0                   0  2821771.0397  1169078.3632     2707   58.57%
                1362890.2694   217  2821771.0397    Cuts:  816     5275   51.70%
                1382312.8193   241  2821771.0397    Cuts:  559     7055   51.01%
                1391797.8184   232  2821771.0397    Cuts:  352     8207   50.68%
                1397651.0290   241  2821771.0397    Cuts:  223     9381   50.47%
                1400255.3875   231  2821771.0397    Cuts:  188    10470   50.38%
*     0+     0                   0  1586020.0063  1400255.3875    10470   11.71%
                1414429.1264   278  1586020.0063    Cuts:  150    12192   10.82%
*     0+     0                   0  1507217.5048  1414429.1264    12192    6.16%
                1430851.3081   227  1507217.5048    Cuts:  254    13843    5.07%
                1432799.6786   254  1507217.5048    Cuts:  150    15036    4.94%

GUB cover cuts applied:  4
Clique cuts applied:  91
Cover cuts applied:  19
Implied bound cuts applied:  278
Flow cuts applied:  439
Flow path cuts applied:  4
Gomory fractional cuts applied: 9

Times (seconds):
Input =  0.144
Solve =  18.552
Output = 0.215
CPLEX 9.0.0: optimal integer solution within mipgap or absmipgap; objective 1507217.505
15036 MIP simplex iterations
```

Estimated optimal value

Result that is returned by the slave optimizer to the master optimizer

Distance from the estimated optimal value

Figure A.1: Evolution of the objective function value in the slave optimization

value, whereas for a configuration implementing a heat pump of type 3 the slave optimization returns a value that lies within 4.94% of the optimal value (and which is therefore less optimal), the result passed over by the slave optimizer to the master optimizer can be better for the configuration with heat pump 2, although initially its COP is worse than that of heat pumps 3a and 3b[2].

According to the above, it is important to notice once again that the Pareto optimal frontier does not in itself provide *the* solution for a given district, but a bunch of solutions which are potentially interesting and that need to be further refined with more sophisticated models for the energy conversion technologies as well as refined optimization parameters.

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[2] The estimation of the optimal value in the slave optimization will be different for both cases, since the COPs for heat pump 2 and heat pumps 3a and 3b are different. However, if all other parameters are equal between both configurations, the two estimations will be less than 5% different.

A.4 Method to define energy consumption profiles

The starting point of the method is to establish a certain number of building categories featuring analogies (date of construction and allocation above all) and for which all the data/information listed in table 6.5 are available for at least one representative member of each category. For each category, the annual fuel consumption per m^2 for the heating and hot water requirements is defined using the following formula [84], in which ID_k^{H} and ID_k^{HW} are the *fuel consumption index* for heating, respectively hot water, of the building, and a_k the proportion of fuel devoted to heating and hot water respectively.

$$ID_k^{\mathrm{H}} = (1 - a_k) \cdot \frac{R_k^{\mathrm{fuel}}}{SRE_k} \qquad [\mathrm{J/year}] \tag{A.4}$$

$$ID_k^{\mathrm{HW}} = a_k \cdot \frac{R_k^{\mathrm{fuel}}}{SRE_k} \qquad [\mathrm{J/year}] \tag{A.5}$$

Values of a_k are evaluated for each category of buildings based on [84]. From equations A.4 and A.5, and the definition of R_k^{fuel}, the yearly heating and hot water requirements in terms of energy can be computed using the thermal efficiency of the boiler implemented in the building:

$$Q_{H,k}^{\mathrm{cons}} = ID_k^{\mathrm{H}} \cdot \epsilon^{\mathrm{boiler}} \qquad [\mathrm{J/year}] \tag{A.6}$$

$$Q_{HW,k}^{\mathrm{cons}} = ID_k^{\mathrm{HW}} \cdot \epsilon^{\mathrm{boiler}} \qquad [\mathrm{J/year}] \tag{A.7}$$

Knowing the total heating energy requirements of a building (equation A.6), the next step is to define the temperature above which no heating is provided to the building anymore, in order to be able to compute the energy signature of this building. To define the temperature above which no heating is provided to the building anymore, T_k^{nh}, a linear regression is computed for each building category, based on the outside temperature and the heating requirements of the buildings for which information was available. This regression was then used to define the temperature T_k^{nh} for all the other buildings. Knowing this temperature, the slope of the energy signature, $s_{H,k}$, can be computed for a given building k, by integrating the outside temperature T_t^{ext} over the time, provided $T_t^{\mathrm{ext}} < T_k^{\mathrm{nh}}$:

$$Q_{H,k}^{\mathrm{cons}} = s_{H,k} \cdot \int\limits_{T_t^{\mathrm{ext}} < T_k^{\mathrm{nh}}} T_t^{\mathrm{ext}} dt + \dot{Q}_{H,k}^{\mathrm{dimen}} \cdot \int\limits_{T_t^{\mathrm{ext}} < T_k^{\mathrm{nh}}} 1 dt \tag{A.8}$$

$$\dot{Q}_{H,k}^{\mathrm{dimen}} = -s_{H,k} \cdot T_k^{\mathrm{nh}} \tag{A.9}$$

$$s_{H,k} = \frac{Q_{H,k}^{\mathrm{cons}}}{\int\limits_{T_t^{\mathrm{ext}} < T_k^{\mathrm{nh}}} T_t^{\mathrm{ext}} dt - T_k^{\mathrm{nh}} \cdot \int\limits_{T_t^{\mathrm{ext}} < T_k^{\mathrm{nh}}} 1 dt} \tag{A.10}$$

Finally, knowing the energy signature for every building in the analysed region, the heating requirements can be computed with help of the meteorological data. For the hot water requirements, it is assumed that they are constant over the year, so that they can easily be computed by knowing $Q_{HW,k}^{\text{cons}}$.

A.5 CO$_2$ diagram

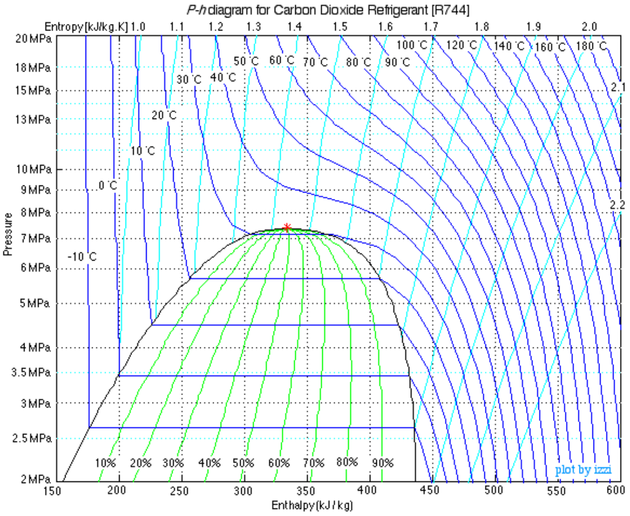

Figure A.2: Pressure-enthalpy diagram of CO$_2$ [92]

A.6 Future work

A.6.1 Cold water network for heating purposes

In Paragraph 5.4.1, the possibility of using only one network (a cold water network) for both cooling and heating is mentioned. In order to make this possible, the superstructure at each node has to be enriched by a heat pump that takes energy in the water of the cold water network, and releases the high temperature energy via the condenser to the building (for heating and hot water purposes). In the model of the slave optimization (model Reseau_07_07_benef.mod), this implies following modifications:

1. Add a term in Equation 4.21 (something like $\dot{Q}_{t,k}^{\text{cold}}$ for instance), that defines the heat provided by the cold water network, via the new heat pump added to the superstructure (add this term on the right of the "=" sign).

2. Define a new constraint that is related to Equation 4.27, and that states that, if the cold water (or cooling) network gives energy to the building (for instance in winter when the new heat pump is operated) $(T_{\mathrm{cr},t} - T_{\mathrm{cs},t}) < 0$. On the other hand, if the cold network takes energy from the building (when it cools the building), then $(T_{\mathrm{cr},t} - T_{\mathrm{cs},t}) > 0$.
3. Take into account the electricity required by the new heat pump by adding an equation similar to Equation 4.42, and don't forget to add this new electricity requirement in the second summation of Equation 4.39 (on the left of the "=" sign).
4. Complete Equations 4.60 to 4.71 with similar equations for the new heat pump.
5. Complete Equations 4.77 to 4.80 with a similar equation for the new heat pump.
6. Add the investment cost for the new heat to the objective function.

Note that since the water can flow in the pipes either way, no major modifications should be necessary regarding this issue.

In the master optimization, changes will have to be done in order to account for the surface water (like it is done for the free cooling). Besides, if a district heat pump is requested to pre-heat the cold water in the winter (for instance to avoid having too large amounts of water circulating through the pipes), this will have to be modelled at the stage of the master optimization too (in the routine called MOO_AMPL_xxx.m).

A.6.2 CO_2 network

In order to be able to use the method for the CO_2 network, the amount of gas or liquid CO_2 requested at each node needs to be computed, to get the gas and liquid consumption profiles. These profiles are then given as input to the model CO2.mod, which is the counterpart of Reseau_07_07_benef.mod for the water network (the model used for the slave optimization). CO2.mod is the model that was used to make the simulations for Section 7.5. This model also includes the possibility of including individual back-up devices. Because the heat cascades are dropped with the CO_2 network (at least n the network level), the slave optimization for the CO_2 network is much easier than for the water network.

Regarding the master optimization, the most difficult thing is to make the thermo-economic models of the plant (district) technologies, since not much data is available for technologies (for instance compressors) operated at the high pressure levels requested.

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Céline Isabelle Weber

Route de Saint-Cergue 40b
1260 NYON
Switzerland

+41 22 361 52 17 (home)
+41 21 693 35 13 (office)

Born on August 22nd 1974, in Geneva, Switzerland.

Swiss citizenship, single.

`celine.weber@epfl.ch`

Following an experience as a production engineer leading a production line in the chemical industry, and a PhD-thesis which led to a patent, I have acquired a global overview of both academics and industry. Enjoying working in challenging environments, and being open-minded and at ease in contacts, I now wish to evolve in the field of energy management.

Professional Experience

From 2003 **Swiss Federal Institute of Technology, Lausanne, Switzerland**
Assistant in the Industrial Energy Systems Laboratory

- *Research activities in the field of rational use of energy*
- *Supervision of students for bachelor and master thesis*
- *Regular organization of the social events such as week-ends in the mountains, a visit at CERN, numerous evenings with various themes*

I developed a software tool to design and optimize the configuration and operation of district energy systems (including combined cycles, gas engines, heat pumps,...), thus decreasing CO_2 emissions and costs. This work resulted in the submission of a patent. I also worked on customer-oriented projects on the energy management of different cities, together with consultant companies. I was invited to present the results at a workshop attended by over 40 people from governmental and private institutions.

2002–2003 **University of Tokyo, Japan**
Research Fellowship in the Department of Chemical Engineering

- *Research activities in the field of building energy systems*

I have focused on the modelling and integration of energy technology devices, and on the integration of these models with a building energy model. I was continually in contact with Japanese companies to get the necessary data.

1998–2001 **Ciba SC, Monthey, Switzerland**
Production manager in the Polymer Division

- *Optimization of the production processes (energy consumption, production time,. . .)*
- *Control of the production costs*
- *Quality management*
- *Optimization and maintenance of the production line*
- *Introduction of new products in the production line*

*I was in charge of a production line having a yearly output of 1000 tonnes of specialty polymers, employing 3 factory workers per shift (3*8 shifts). I ensured the timely and high quality standard production of existing products, I introduced new products, and I took part at the transfer of a whole product range to another production site. I was also member of the production site representatives to the headquarters.*

1997 **Burri A.G., Malters, Switzerland**
(1 month) **Trainee**

- *Preliminary investigation and requirement specification for the implementation of a computer based performance oriented salary system*

1996 **Professional nurse school, Zurich, Switzerland**
(2 months) **Trainee**

- *Preliminary investigation and requirement specification for the implementation of a quality management system in the school*

1996 **Du Pont de Nemours (Luxemburg) S.A., Contern, Luxemburg**
(4 months) **Trainee**

- *Coordination of a research mandate given to a consultant company*
- *Analysis of manufacturing defects*
- *Comparison of security standards*

1994 **Bobst S.A., Prilly, Switzerland**
(1 month) **Trainee**

- *Machining*

Education

From 2003	PhD thesis (ongoing), Swiss Federal Institute of Technology, Lausanne, Switzerland, Industrial Energy Systems Laboratory
2001	Swissair pilot school (stopped untimely due to the bankruptcy of Swissair)
1998	Master thesis, Swiss Federal Institute of Technology, Zurich, Switzerland, Institute for Production and Process Engineering
1992	Swiss Federal Maturity and Latin-English Baccalaureate, Nyon, Switzerland

Languages (bilingual)

French: Mother tongue
Swiss-German: Mother tongue
German: Very good
English: Very good
Japanese: Beginner

Computing skills

Platforms: Linux, Windows
Programming Languages: Matlab, AMPL (Cplex), Unix shell scripts
Tools: LaTeX, MS office, emacs

Interests and Hobbies

- Student representative (1994-1998)
- Comity member of the Academic Association for Chamber Music (ongoing)
- Flute: non-professional flute diploma at the Academy of Music in Lausanne, Switzerland (obtained in May 2001); play regularly with professional musicians in concerts
- Single engine aircraft: private pilot license (obtained in December 1994)
- Sports: Hiking in mountains, Swimming, Skiing