ENVIRONOMIC OPTIMIZATION OF DISTRICT HEATING NETWORK SYSTEMS WITH BOTH CENTRALIZED AND DECENTRALIZED HEAT PUMPS

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1. SUMMARY

In Switzerland like in many countries, many of the populated areas are located close to lakes or rivers, offering a large potential for the use of heat pumps. Although district heating is an obvious solution, adapting the delivery temperature to the most exigent users is detrimental to overall system performance. The best system configuration could avoid this pitfall by relying on a centralized plant of heat pumps with cogeneration, supplemented by decentralized heat pumps for the more demanding users.

Using expert knowledge to compose a superconfiguration of all possible components for a district heating network system with both centralized and decentralized heat pumps, a novel methodology is proposed for modeling and optimizing, under known sets of economic, user characteristic and environmental constraint data, both the final configuration resulting from the superconfiguration as well as the configuration's corresponding component designs. The optimization is accomplished with the help of a cutting-edge operations research tool, a genetic algorithm, while the model itself is based on a total cost objective function which unifies in a single model investment, operation, and pollution costs. These latter costs are (for each of the major pollutants) based on the literature as well as on continuous pollution penalty functions adapted to system emissions and to local immissions ratios. These penalties are included to help guide the choice of configuration and component designs away from regions where pollution limits or undesirable levels of actual emissions in combination with local / global conditions are approached too closely.

Results are shown for various user distributions and fuel and electricity prices. A comparison between the results found with and without taking into account pollution is also presented.

2. INTRODUCTION

In Switzerland like in many countries, the demand for space heating contributes greatly to the total energy demand. Since at present heat pumps satisfy only a very small fraction of the heating demand, the heating efficiency predominantly reflects contributions from conventional heating systems and is by definition limited to less than 100%. With heat pump technology, the efficiency of conversion or, more appropriately, coefficient of performance (COP), may, in fact, exceed 100% due to the heat pump's ability to utilize the free-energy available from the environment. The COP for these types of devices is defined as the ratio between the useful energy and the non-free energy required to generate it. For electrically driven heat pumps and taking into account energy conversion efficiencies for electricity generation, transmission and distribution, heat pump COPs vary between about 103% using nuclear generated electricity to about 270% using hydro-electricity [1].

The use of heat pumps, however, depends on the existence of adequate heat sources such as lakes, rivers, and other large bodies of water. These are very good due to their stable temperature levels, good heat transfer characteristics, and general abundance while using the atmosphere is somewhat less desirable. When coupled with district heating systems (DHS), high heat pump conversion rates and the advantages of using DHS lead to very competitive solutions for meeting heating needs. The most important advantages include the security of the energy supply, improvements in energy conversion efficiencies with positive consequences for

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the environment, and proportional reductions in capital costs (at least in terms of energy generation) due to the scaling which results from the use of a centralized heating plant. The same arguments are valid for district cooling. However, the overall higher fixed or capital costs of such systems are often used as an argument against DHS. This can be overcome in part by combining district heating and cooling with a consequent and significant reduction in equipment costs. In fact, when coupled with energy efficient technologies, the advantages listed above as well as the higher fixed costs have a tendency with respect to resource price fluctuations to stabilize the heating prices which the consumer sees over time. Since the majority of the most important urban areas are located near big water reservoirs, heat pump district heating and cooling networks have a good potential for development in the medium-term.

3. ENVIRONOMIC MODEL: GENERAL CONSIDERATIONS

Although district heating in and of itself is an obvious solution, adapting the delivery temperature to the most exigent users is detrimental to overall system performance. This pitfall can be avoided by relying on a centralized plant of heat pumps with cogeneration, supplemented by decentralized heat pumps for the more demanding users [2]. The difficulty, of course, which arises is determining which configuration and design best meet all the user demands, especially since a large number of possible system configurations and component designs exist which can do so. Things are complicated further when not only technical considerations but both economic and environmental considerations must be taken into account. The possible number of degrees of freedom (independent or decision variables) which exist is large and presents for the engineer the daunting if not impossible task of adequately, much less optimally, determining the best system for the job.

To aid in this task, a modeling and optimization methodology has been developed and applied to the synthesis (choice of system configuration) and design (choice of component capacities) of a district heating system with both centralized and decentralized heat pumps (DH-HP/COGEN system). The resulting model called an *environomic* model [3-5] (an extension of the classical *thermoeconomic* model [e.g., 6-8]) derives from a unified approach for simultaneously taking into account the thermodynamic, economic and environmental aspects of the system. This type of model when fully developed includes those thermodynamic, economic and environmental characteristics associated with the entire life cycle of a system beginning with the manufacture of its capital equipment, on through the operation of the system itself and ending with the dismantling of the system's capital equipment. The introduction of life cycle and environmental considerations into an overall model is an attempt to respond during the synthesis, design and operation of an energy system to the concept of sustainability [9]. Such a model coupled to a deterministic or non-deterministic optimization algorithm permits one to mathematically search for the optimum solution from the continuous, non-contiguous (linear or non-linear) space of possible solutions. Simple analysis of the model allows one to examine this space and determine trends of the decision variables towards this optimum.

The model in general is represented by an optimization criteria called an objective function and by a set of decision variables and equality and inequality constraints which describe the synthesis, design and operation of the system being modeled. The objective function for such an environomic approach represents the sum of costs (physical or monetary) incurred by the system during its entire lifetime. The model itself describes the space of possible solutions. The global optimum within this space corresponds to the global minimum of this objective function.

Under steady state considerations, a general statement of the environomic model is given by the following environomic formulation, from which a purely thermoeconomic model can be derived as a special case (for complete details of how each of these terms is developed, the reader is referred to Ref. [11]):

$$\text{minimize } \dot{C}_{\text{total net}}(\vec{x},\vec{y}) = \dot{C}'_{\text{equip}}(\vec{x},\vec{y}) + \dot{C}'_{\text{res}}(\vec{x},\vec{y}) + \dot{C}_{\text{pol}}(\vec{x},\vec{y}) - \dot{B}_{\text{prod}}(\vec{x},\vec{y}) + \dot{K} \quad (1)$$

$$\text{w.r.t. } \vec{x} \text{ and subject to:} \quad h_j(\vec{x},\vec{y}) = 0 \quad j = 1,\ldots,J \quad (2)$$

$$g_k(\vec{x},\vec{y}) \geq 0 \quad k = 1,\ldots,K \quad (3)$$

$$\text{where} \quad \vec{x} = (x_1, x_2, \ldots, x_I) \quad (4)$$

$$\vec{y} = (y_1, y_2, \ldots, y_J) \quad (5)$$

$$x_{i\_\min} < x_i < x_{i\_\max} \quad i = 1,\ldots,I \quad (6)$$

$$y_{j\_\min} < y_j < y_{j\_\max} \quad j = 1,\ldots,J \quad (7)$$

where $\dot{C}'_{equip}$ is the sum of extended equipment costs, $\dot{C}'_{res}$ is the sum of the extended resource (those used in the operation of the system) costs, $\dot{C}_{pol}$ is the sum of the pollution costs associated with the operation of the system, $\dot{B}_{prod}$ is the sum of the revenues derived from the operating the system, and $\dot{K}$ is the sum of fixed costs (i.e. those independent of system operation). The extended costs $\dot{C}'_{equip}$ and $\dot{C}'_{res}$ are thus named because in addition to the specific costs of each piece of equipment or resource, both life cycle and environmental costs may be included.

The $\vec{x}$ above represent the independent or decision variables (degrees of freedom) for the model while $\vec{y}$ represent the dependent variables. The equality constraints describe the mass and energy (exergy) balances which the system obeys as well as any component performance characteristics which may be present. Physical limits on the system are handled by the inequality constraints. When time is a factor, the environomic formulation presented here can be treated as described in Ref. [10].

In this paper, not all the possible environmental and life cycle aspects associated with the DH-HP/COGEN system's environomic model are considered. Those which are, include the NO_x and CO_2 emissions emanating during the manufacture and dismantling of the capital equipment (taken into account in $\dot{C}'_{equip}$), those occurring during the operation of the system (taken into account in $\dot{C}_{pol}$), as well as those associated with the production and delivery of the resources (fuel and electricity) used by the DH-HP/COGEN system (taken into account in $\dot{C}'_{res}$) [12]. The pollution costs which are considered are (for each of the major pollutants) based on the literature as well as on continuous pollution penalty functions adapted to system emissions and to local immissions ratios. These penalties are included to help guide the choice of configuration and component designs away from regions where pollution limits or undesirable levels of actual emissions in combination with local / global conditions are approached too closely.

4. ENVIRONOMIC MODEL: SUPERCONFIGURATION

A general schematic of the DH-HP/COGEN system modeled is shown in Fig. 1. It includes a central plant, the main distribution network, and the users connected to the main network. As shown, the model includes the energy preparation chains leading to the primary energy resources used by the system. The system's network delivers energy to meet user's heating loads in winter and domestic hot water throughout the year.

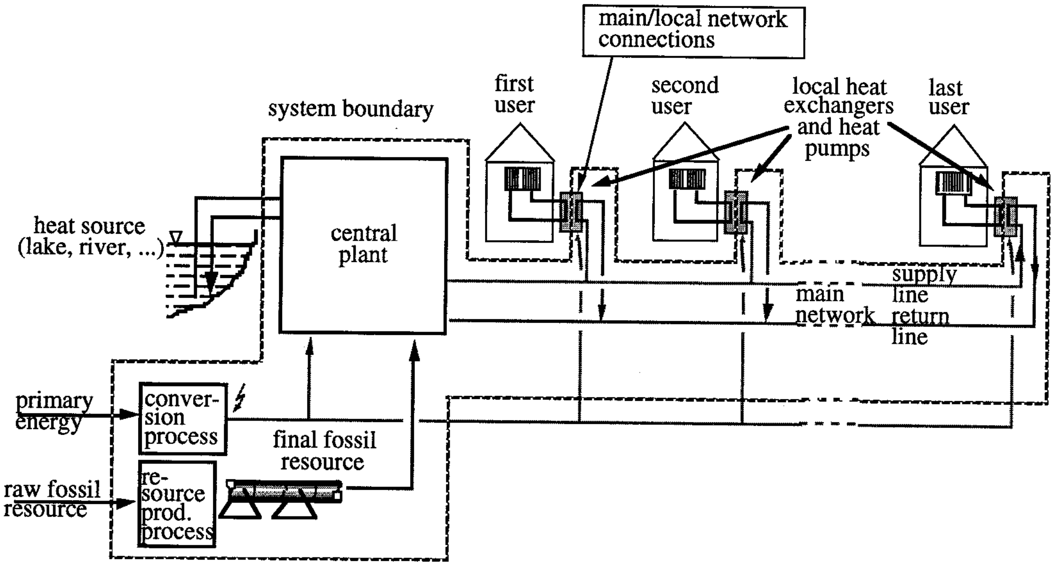

Fig. 1 - A general schematic of the DH-HP/COGEN system modeled.

The central plant superconfiguration includes one heat pump, one cogeneration gas reciprocating engine unit, one gas turbine cogeneration unit and one gas furnace. The heat pump works between the heat source (river, lake, etc.) and the distribution network. It driven by an electrical motor, with the electricity taken either from the utility grid or generated by the plant itself employing the cogeneration units. These cogeneration units provide additional heat to the distribution network, thanks to the engine's water and lubrication oil cooling as well as the heat recuperated from the engine's and/or turbine's exhaust gases. A furnace is also present in the superconfiguration and serves as a complement or as an alternative to the other units. Since the heat pump's efficiency is strongly influenced by the condensation temperature, it is placed in the system so that the rate of heat which it supplies is in a lower temperature range than that for the cogeneration unit(s) and the furnace (i.e. the heat pumps are inserted upstream of these other units). Fig. 2 illustrates the schematic for the superconfiguration of the DH-HP/COGEN system's central plant.

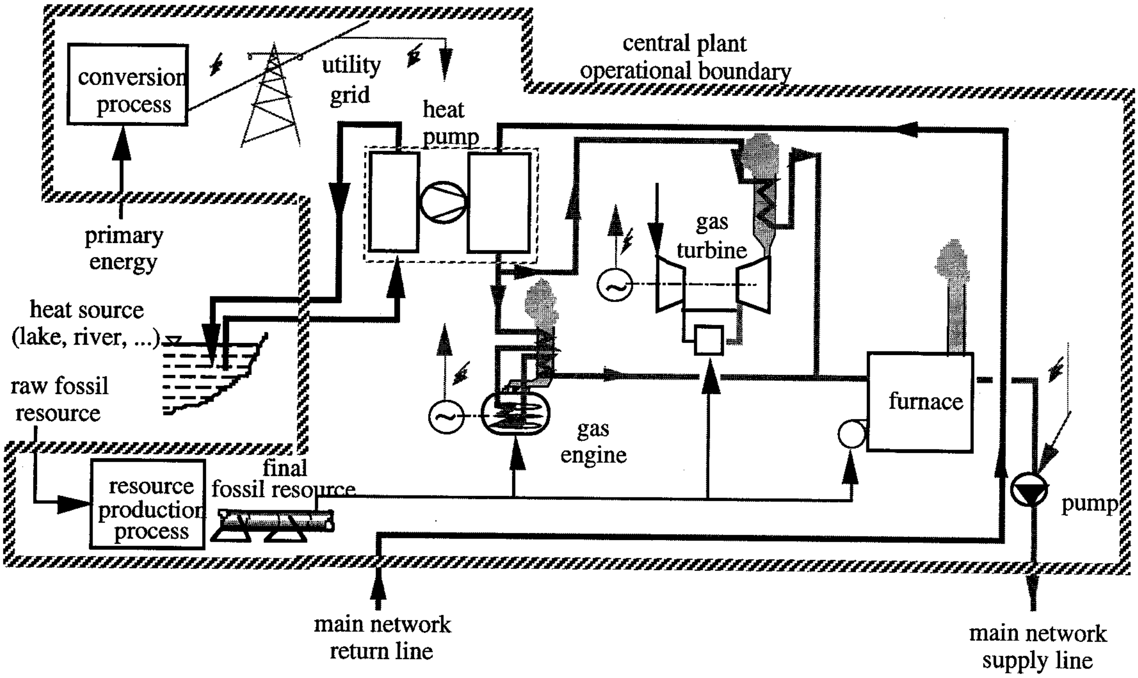

Fig. 2 - A schematic for the superconfiguration of the DH-HP/COGEN system's central plant.

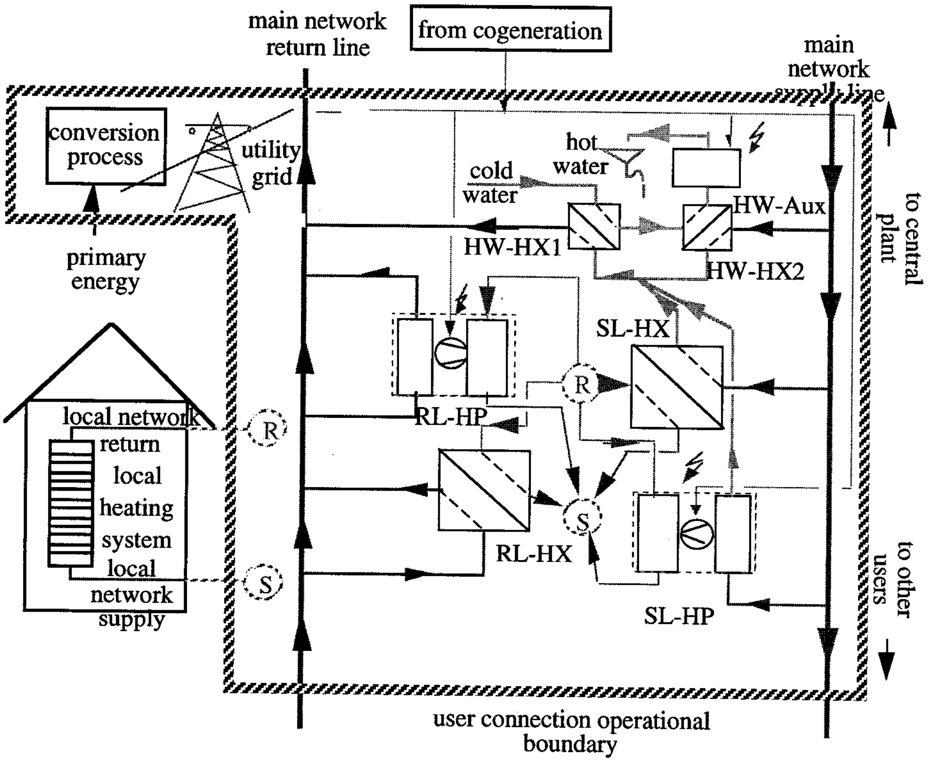

Fig. 3 - A schematic of the superconfiguration for a DH HP/COGEN system

In addition to the central plant, the superconfiguration provides a number of options for transferring heat between the main distribution network and the local building or user network. It also includes options for domestic hot water preheating and heating. If the local network has a supply temperature sufficiently lower than that of the main network, a simple heat exchanger assures the right amount of heat to the user. Otherwise, a heat pump is employed locally with its evaporator fed by the network's main line and its condenser supplying heat to the user's local network.

If, on the other hand, the temperature of the return line fluid for the main distribution network is high enough, a heat exchanger can be used to connect the main network return line and the local network. An additional option is to connect a heat pump between the main network return line and the local user network. The advantage of using the return line in this fashion is that the main network return temperature at the plant is lower, thus improving the efficiencies of the central plant's heat pump. Another consequence of this lower return temperature is a decrease in the main network mass flow rate, thus diminishing the network costs of investment and operation (water pumping). Fig. 3 illustrates the user connection options in the system superconfiguration. Users (i.e. user blocks) as described by the figure above are connected one after the other on the network. Each block represents a group of local users with similar heating and hot water demands. Note that the superconfiguration's last user block does not include any element choices (heat exchanger and heat pump) on the return line.

The environomic system model represents all superconfiguration units thermodynamically as opposed to through a set of performance characteristics. The heat pump models are based on the simulation of thermodynamic heat pump cycles, with two stages for the central unit and a single stage for the users' heat pumps. The models for the cogeneration units are based on constant isentropic efficiencies for the turbomachinery components of the gas turbine and on a constant mechanical efficiency for the gas engine. The cogeneration heat rate is based on a specific calculation, using fixed pinches, of the heat exchange between the exhaust gases and the water of the network.

Finally, the superconfiguration described above is not exhaustive. Other elements could be included in the model and other ways of connecting the elements are possible. For example, more than one type of heat pump could be included, in order to have a choice between different technologies. For a sufficiently complicated system, however, no superconfiguration can or necessarily should be totally complete for two reasons: i) expert knowledge used judiciously can eliminate a number of options a priori which though physically feasible are of little interest to the engineer and ii) the more complicated the model is, the more difficult or in fact even impossible finding a solution becomes since the types of models considered are typically highly non-linear and involve a high number of degrees of freedom.

5. ENVIRONOMIC MODEL: OPTIMIZATION

Optimizing the DH-HP/COGEN system's environomic model is a difficult task due to its complexity (e.g. thirty-four independent variables and many infeasible regions). The resulting optimization problem is ideally of the type: mixed integer non-linear programming (MINLP), even though in the methodology described in this paper only real variables are used. Effectively searching the multi-dimensional space of feasible solutions described by this problem and arriving at the global optimum (i.e. the configuration and set of component designs which optimally meet all demands placed on the system) requires both a powerful algorithm and sufficient computing power. A deterministic or geometric (gradient) based approach to solving this problem [13] is perhaps possible, but would handicap the generality of the methodology used to develop the environomic model presented here.

In contrast, non-deterministic or heuristic approaches use neither gradients in particular nor geometry in general to search out the global optimum. Thus, they are less likely to be tricked into finding local optima and are more comprehensive in thoroughly searching the region of all feasible solutions. Heuristic approaches which have shown a great deal of promise are genetic algorithms (GAs). These algorithms simulate the process of evolution with the "survival of the fittest" principle as the driving force and key biological concepts such as populations, generations, mating, and mutation as the corner stones of the procedure. In addition, when combined with our environomic modeling methodology, GAs do not exhibit the same limiting feature mentioned above for deterministic approaches. Thus, a Struggle GA, developed at MIT [14] and adapted at the Ecole Polytechnique Fédérale de Lausanne [15], was used to solve the environomic synthesis and design optimization problem formulated here. It should be noted that the GA used here, and in particular the crossover operator (Blend

6. RESULTS AND DISCUSSION

A major failure of many databases on the heating needs of buildings or areas of cities is that they refer only to energy or heat rate values without a proper documentation of the actual heating temperature required. Although most buildings in existing city areas have been designed for the typical hydronic radiator heating range of 70 to 90°C, overdesign and recent improvements of building envelopes have contributed in many instances to significantly reducing actual temperature requirements. This was confirmed by a recent investigation of the buildings in a relatively old part of Lausanne (CH) supplied primarily by oil-fired central heating systems [16]. Table I shows the actual heating needs of all users in this part of Lausanne divided into four major categories on the basis of their temperature requirements. This user distribution is used as a reference case for the optimization results which appear in Tables II to VII below.

In determining the optimum DH-HP/COGEN system configuration and component designs for various resource scenarios (e.g., fuel and electricity prices), operational sequences as a function of seasonal heating demand variations are taken into account by multiplying the nominal operational energy values and costs by operational factors. The latter are functions of the expected average yearly contribution of each major component. Based on the cumulated heat rate demand curve, supply contributions are determined from a strategy giving priority to the central plant's heat pump (if chosen), followed by the cogeneration unit, and then by the furnace.

For the present set of results, selling electricity to the outside grid was not allowed. When electricity required by the heat pump was provided by cogeneration, the capacity of both units was modulated simultaneously in order to prevent wasting thermal energy.

TABLE I

Typical heating demand for an area of the city of Lausanne (CH) [15].

category of building	temperature to and from the local heating system at maximum heat demand [°C]	Maximum heat demand [MW]
category 1	46 - 36	2.85
category 2	57 - 50	5.70
category 3	67 -58	39.9
category 4	78 - 66	8.55

The first set of results seen in Tables II and III and Fig. 4 show configurations and component designs optimized on the basis of a moderate, constant price for electricity (13 CHcts/kWhel) as well as on the basis of three different prices for natural gas covering a broad range of potential market conditions. Results are shown with (i.e. environomic model) or without (i.e. thermoeconomic model) internalization of the pollution costs for the two main pollutants, NO_x and CO_2.

TABLE II

Optimized nominal heat rates of the main system components.

	Nominal heat rate [MW]					
electricity price 13 CHcts/kWh	**without pollution costs**			**with pollution costs**		
gas price [CHcts/kWh]	**2.0**	**4.5**	**7.0**	**2.0**	**4.5**	**7.0**
Network Temper. [°C]	97.0	96.9	85.9	96.9	84.8	82.6
Heat Pump	0.0	28.2	51.3	26.70	62.65	62.69
Cogeneration Gas Turb.	0.0	13.7	0.00	12.97	0.00	0.00
Cogeneration Gas Eng.	0.18	0.00	0.00	0.00	0.00	0.00
Gas Furnace	62.5	20.8	11.4	23.03	0.05	0.00

At the lowest gas price (2 CHcts/kWh LHV), the thermoeconomic optimum provides a configuration which relies on a furnace to satisfy all the heating needs (62.5 MWth), those furnished by a small cogeneration gas engine which produces the electricity consumed by the plant internally (for the pumps primarily). The supply temperature corresponds to the maximum value admitted in the model (97°C) since with combustion in a single furnace dominant, there is little incentive to further reduce the temperature by recovering a minute part of the combustion gas energy at the expense of increased network and user equipment costs.

TABLE III

Cost breakdown of the unit of heating energy delivered.

	Cost Breakdown [CHcts/kWh]					
electricity: 13 CHcts/kWh	**without pollution costs**			**with pollution costs**		
gas price [CHcts/kWh]	**2.0**	**4.5**	**7.0**	**2.0**	**4.5**	**7.0**
building	0.57	0.77	0.66	0.77	0.56	0.56
equipment	0.42	1.31	1.11	1.28	1.16	1.17
network	0.97	1.00	1.07	1.04	1.12	1.14
administration	1.18	1.18	1.18	1.18	1.18	1.18
energy	2.09	2.53	3.73	1.14	3.80	3.77
pollution	0.00	0.00	0.00	2.01	0.08	0.08
Total	5.23	6.79	7.74	7.42	7.90	7.90

In contrast, the environomic model results in a furnace reduced to a little more than one third of that when pollution is not taken into account. The remaining heat demand is provided by a heat pump and a cogeneration gas turbine sized to provide the electricity needed by the plant (HP+pumps). The network temperature rests as before at its maximum value.

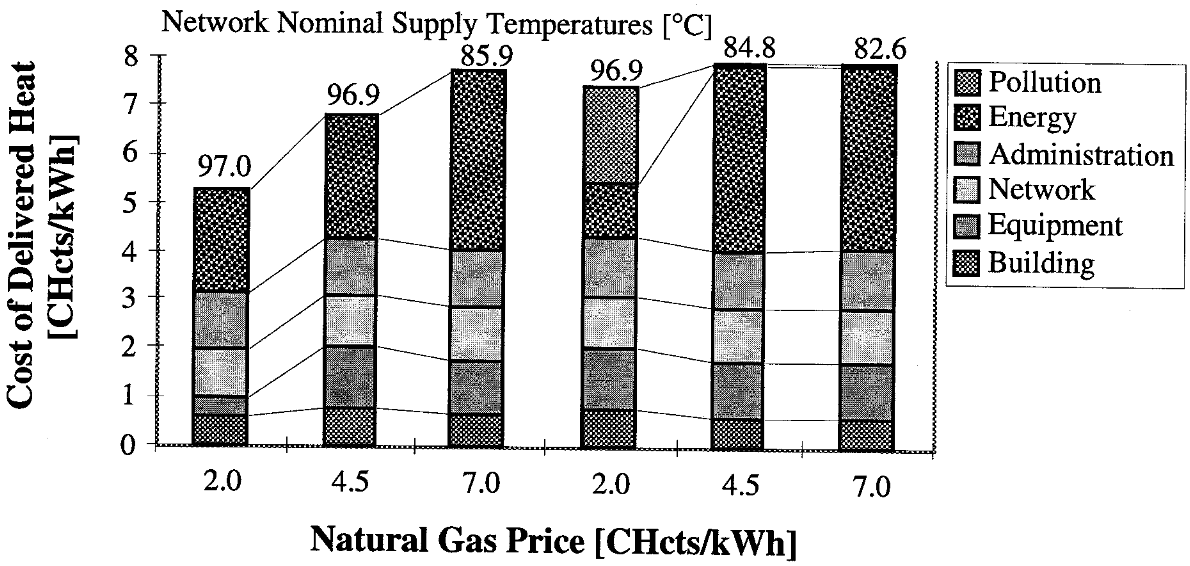

Fig. 4 - Cost breakdown of the optimized system as a function of the price of natural gas and with or without pollution costs (electricity price = 13 CHcts/KWh).

This solution also prevails for the case of an intermediate gas price of 4 CHcts/kWh and no pollution considerations (thermoeconomic model). However, with pollution, a heat pump fed by electricity from the grid is chosen to deliver almost all the heat required and the network temperature is dropped accordingly to 85°C.

For a very high gas price (7 CHcts/kWh), the optimal solution for the thermoeconomic model is a heat pump using grid electricity and satisfying about 80% of the heat demand while a furnace provides the rest at a moderate network temperature of 86°C. With pollution, the gas furnace is eliminated and the temperature is further reduced to 83°C.

For reference, Table IV shows a cost breakdown for the solution with a lone furnace and a gas price of 2 CHcts /kWh LHV. Costs with and without internalized pollution costs included are the solution with a heat pump, cogeneration unit and furnace given in Table III, a result which is expected.

TABLE IV

Cost breakdown of the unit of delivered heating energy from a system which includes a lone gas furnace (for a unit gas price of 3.5 CHcts/KWh)

Reference case: Lone Gas Furnace Gas price: 2.0 CHcts/kWh		
Cost Breakdown [CHcts/kWh]		
Pollution costs	**no**	**yes**
building	0.57	0.56
equipment	0.42	0.33
network	0.97	1.01
administration	1.18	1.18
energy	2.09	2.14
pollution	0.00	2.30
Total	5.23	7.51

TABLE V

Pollution unit costs [17]

Emitted substance	Unitary Cost [CHF/kg]
NO_x	13.8
CO_2	0.0420

Tables VI and VII illustrate the environomic model solution obtained at 4.5 CHcts/kWh when the distribution of users is modified by exchanging the heat demand percentage of the lowest and highest temperature users (categories 1 and 4, Table I) and keeping the others constant. The optimum network temperature drops even further and a decentralized heat pump is chosen to satisfy the now marginal high temperature users.

TABLE VI

TABLE VII

These tables are valid for the case of a relatively small rate of heat demand at high temperature (2.85 MW at 78°C) and a higher rate of heat demand at low temperature (8.55 MW at 78°C)

Optimized nominal heat rate of the main components of the system

	Nominal heat rate [MW]	
Prices [CHcts/kWh]: **Electricity: 13** **Gas: 4.5**	**without pollution costs**	**with pollution costs**
Network Temper. [°C]	97.0	76.41
Heat Pump	27.3	62.42
Cogener. Gas Turb.	12.6	0.00
Cogener. Gas Eng.	0.00	0.00
Gas Furnace	22.8	0.00

Cost breakdown of the unit of delivered heating energy

Electricity: 13 CHcts/kWh Gas price: 4.5 CHcts/kWh		
Cost Breakdown [CHcts/kWh]		
Pollution costs	**no**	**yes**
building	0.77	0.56
equipment	1.28	1.21
network	0.97	1.14
administration	1.18	1.18
energy	2.47	3.61
pollution	0.00	0.07
Total	6.66	7.78

For all the results presented above, the pollution penalty factors, used are on the order of 1.5 for CO_2 and 3.2 for NO_x. This heavier penalty for NO_x results from the fact that the central plant for the district heating network is, by nature, located in an urban environment. Given the fact that Swiss norms for NO_x emitted by gas turbines are higher per unit of gas consumed than for furnaces, NO_x pollution costs play a significant role in the pollution costs of cogeneration gas turbines or engines. As a result of this difference in penalties and norms, the pollution costs between configurations are sensitive to the technology used but not directly

7. CONCLUSIONS

Environomic approaches like the one demonstrated in this paper, coupled with powerful modern algorithms, considerably extend the range of tools available to the engineer working on the optimization of complex energy systems. When applied to district heating with both decentralized and centralized heat pumps as well as cogeneration units, such an approach can not only help the identification and selection of innovative configurations but also illustrate and quantify the environmental benefits of heat pumps as an alternative technology for this important domain of energy usage.

Future steps in the study include a truly time-dependent optimization of the operation as well as the extension of the model to also satisfy a cooling demand with for example a four-pipes network (one pair for heating and one pair for cooling).

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