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An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: Methodology

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Abstract — Although heat pump based district heating is often an obvious solution from an energy standpoint, adapting the delivery temperature to the most exigent users is detrimental to overall system performance. This pitfall can be avoided with a centralized plant of heat pumps, cogeneration units and an auxiliary furnace, supplemented by decentralized heat pumps. However, the problem of mixed energy production and delivery which this poses is complex and presents for the engineer the daunting if not impossible task of adequately, much less optimally, determining the best system for the job. In this first of a series of two articles, a general environomic methodology for aiding in this task is described, which includes models of the thermodynamic, economic, and environmental characteristics of the system considered. The system's environmental characteristics are introduced into the model through pollution damage cost terms and a new form of pollution penalty functions, which adapt to the system's changing emissions and to local and global pollutant conditions. The superstructure of a district heating system with cogeneration and heat pumps (centralized or not) is presented and discussed. Optimization results are presented in the accompanying article [1]. © 2000 Éditions scientifiques et médicales Elsevier SAS

energy / exergy / environment / economics / environomics / optimization / district heating / heat pump / pollution

Résumé — Approche «environomique» pour la modélisation et l'optimisation d'un réseau de chauffage urbain utilisant des systèmes centralisés et décentralisés de pompes à chaleur, cogénérateurs et/ou chaudières à gaz. 1re partie : Méthodologie. Les réseaux de chauffage à distance alimentés par pompes à chaleur représentent une solution attractive du point de vue énergétique, mais le fait d'adapter la température de réseau à l'utilisateur le plus exigeant a une influence négative sur les performances du système. Cet inconvénient peut être évité en considérant la possibilité d'inclure des pompes à chaleur décentralisées en plus de la centrale qui, en toute généralité, peut comprendre une ou des unités de pompe à chaleur, de cogénération ou de chaudières. Cependant le problème de la conception d'un tel système de production mixte devient complexe et ce caractère est encore plus marqué lorsque le souhait existe d'optimiser en considérant également les bénéfices environnementaux qui constituent une des motivations importantes pour le développement de tels systèmes à l'avenir. Ce premier article d'une série de deux articles décrit une méthode générale, dite «environomique», de conception de systèmes énergétiques complexes. Cette méthode comprend la modélisation des caractéristiques thermodynamiques, économiques et environnementales de tels systèmes. Les caractéristiques environnementales sont introduites au moyen de termes de coûts de pollution et d'une nouvelle forme de fonctions de pénalité associées aux différentes émissions qui tiennent compte des conditions locales et globales. La superstructure d'un système de chauffage urbain avec cogénération et pompes à chaleur (centralisée ou pas) est présentée et discutée. Les résultats d'optimisation sont présentés dans l'article suivant [1]. © 2000 Éditions scientifiques et médicales Elsevier SAS

énergie / exergie / environnement / économique / environomique / optimisation / chauffage urbain / pompe à chaleur / pollution

Nomenclature

Aux	auxiliary	
B	sum of the revenues from the products delivered	CHF

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C	cost	CHF or J
c	specific costs	$CHF \cdot kg^{-1}$
c	concentration	$kg \cdot m^{-3}$
Cen	central plant	
DHN	district heating network	
Ex	exergy	J
f	penalty factor	
g	inequality function	
GA	gas engine	
GT	gas turbine	
GF	gas furnace	
h	equality function	
HP	heat pump	
HDW	hot water	
HX	heat exchanger	
K	sum of the fixed costs	CHF
M	mass	kg
$\dot{M}$	massflow	$kg \cdot s^{-1}$
MINLP	mixed integer nonlinear programming	
N	number	
P	pollution function	
$\dot{p}$	pollutant flowrate	$kg \cdot s^{-1}$
Q	heat	J
RL	return line	
S	entropy	$kJ \cdot K^{-1}$
s	specific entropy	$kJ \cdot kg^{-1} \cdot K^{-1}$
SL	supply line	
T	temperature	K
x	independent variable	
y	dependent variable	
V	volume	m^3
$\dot{V}$	volume flowrate	$m^3 \cdot s^{-1}$

Greek symbols

$\dot{\phi}$	environmental pollution rate	$J \cdot K^{-1} \cdot s^{-1} \cdot m^{-3}$
κ	pollutant level	$J \cdot K^{-1} \cdot m^{-3}$
Π	new pollution function	

Subscripts

0	reference (or environment)
$0i$	current condition
$0i$–nat	natural or pure state
a	amortization
c	critical
e	exhaust gas
equip	equipment
in	entering the system
$in\pi$	concerning process π
$ir\pi$	concerning substance i of process π and resource r
man	manufacturing chain for the equipment of the system
me	material entering the system
mx	material exiting the system at the end of life
n	designation of a given component
op	operating
out	exiting the system
pol	pollution
pol_equip	pollution linked to the manufacture of equipment
pol_res	pollution linked to the preparation of the resources
prod	production
pt	resource preparation
res	resources
rem	chain of processes for removing the equipment at the end of life
total net	total
uQ	user heat
uE	user electricity

1. INTRODUCTION

While during the seventies, public attention was focused mainly on fossil resource scarcity, today's concerns are related primarily to the impact that their use in the long term may have on the environment. This is illustrated, for example, by the fear that the growing concentration of carbon dioxide augmented by human activity may be contributing to global warming. These same activities lead to emissions of other harmful substances as well. To complicate things further, economic growth of developing countries is expected to increase pressure on the Earth's environment. Two of the key factors for dealing with these concerns while meeting growing demands for energy are improved energy efficiencies and more environmentally benign energy production systems [2, 3].

The demand for space heating contributes greatly to total energy demand in many industrialized countries. The heating efficiency of conventional heating systems (e.g., individual furnaces) is by definition limited to less than 100 %. As it is well known with heat pump technology, the efficiency of conversion or more appropriately, the coefficient of performance (COP) exceeds 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 nonfree energy required to generate it. Among the possible heat sources, lakes, rivers, and other large bodies of water, are very good due to their stable temperature levels, good heat transfer characteristics, and general abundance. Note also that populated areas are often located close to lakes or rivers, offering a large potential for the use of heat pumps. The temperatures of the sources used play a central role in the performance characteristics of a heat pump system. In particular, the smaller the temperature difference between source and sink (user), the higher the heat pump's COP is.

In order to meet the demand for space heating, district heating networks (DHNs) play, if not a central role, a larger and larger one in many countries. However, oftentimes, all users are connected to the network by means of heat exchangers, a characteristic which introduces a serious limit for heat pump based DHNs serving a variety of different building typologies [2]. This is due to the fact that the network supply temperature must be greater than that of the highest local heating network temperature (belonging to the "most exigent user") delivered by the DHN. This limit could be circumvented by the introduction, at least for the most exigent users, of local heat pumps working between the DHN and the local (e.g., building) heating networks [4, 5]. Furthermore, when the DHN return temperature is high enough, one or more users can be connected by heat exchangers to the return line of the DHN. A heat pump could also be inserted between the DHN return line and a local heating network. The main advantage of the lower return temperature is a decrease in the DHN mass flow rate, thus, diminishing the network costs of investment and operation (pumping). It also offers the possibility to add customers once the network is built (and saturated). Another side advantage of using the return line as a cold source for decentralized heat pumps is that the DHN return temperature at the plant is lower, thus, improving the efficiencies of the central plant's heat pump(s) (even if more power is requested for the decentralized heat pump).

The possible number of degrees of freedom (or the number of independent or decision variables) for the problem of mixed energy production and delivery posed above 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 DHN with both centralized and decentralized heat pumps. The resulting model called an *environomic* model [6–8] simultaneously takes into account the thermodynamic, economic and environmental characteristics of the system. This type of model when fully developed includes those thermodynamic, economic and environmental aspects associated with the entire life cycle of a system beginning with the manufacture of its equipment (including resource extraction, parts fabrication, equipment assembly, transport and installation), continuing with its operation and ending with equipment removal (dismantling, recycling, and/or disposal). The objective of the model, i.e. the criterion used to optimize the system's synthesis, design and/or operation, is expressed either in monetary or in physical (exergetic) units. Such a model, coupled with an optimization scheme, permits one to mathematically search for the optimal solution within the space of all possible solutions and responds in part to the concept of sustainability during the development of a new or the operation of an existing system.

[2] In Central Europe, heating networks for old buildings were designed for high working temperatures, while modern buildings are equipped with lower temperature networks.

2. ENVIRONOMIC MODEL

The environomic model in general is represented by an extension of the classical thermoeconomic model, e.g., [9–11]. Such a model is represented by an optimization criterion 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. Since the sum of costs represents the principle value of interest for the stakeholders involved in the decision-making process of a project, this sum is taken here as the common base for this criterion. In fact, it is the sum of costs (physical or monetary) incurred by the system during its entire lifetime [12].

Under steady state conditions, a general statement of the environomic optimization problem is given by the following formulation, from which a purely thermoeconomic model can be derived as a special case [13]: minimize

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

w.r.t. $\boldsymbol{x}$ and subject to:

$$h_j(\boldsymbol{x},\boldsymbol{y}) = 0, \quad j = 1,\ldots,J \tag{2}$$

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

where

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_I) \tag{4}$$

$$\boldsymbol{y} = (y_1, y_2, \ldots, y_J) \tag{5}$$

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

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

$\dot{C}'_{\text{equip}}$ is the sum of augmented equipment cost rates and $\dot{C}'_{\text{res}}$ the sum of augmented resource cost rates (resulting from the operation of the system) defined by

$$\dot{C}'_{\text{equip}} = \dot{C}_{\text{equip}} + \dot{C}_{\text{pol\_equip}} \tag{8}$$

$$\dot{C}'_{\text{res}} = \dot{C}_{\text{res}} + \dot{C}_{\text{pol\_res}} \tag{9}$$

In equations (8) and (9), $\dot{C}_{\text{equip}}$ represents the sum of traditional cost rates associated with the capital equipment, $\dot{C}_{\text{res}}$ the sum of cost rates associated with the resources used by the system for its operation, while $\dot{C}_{\text{pol\_equip}}$ and $\dot{C}_{\text{pol\_res}}$ are the sum of pollution cost rates associated, respectively, with system equipment manufacture and removal and with resource preparation and transport. $\dot{C}_{\text{pol}}$ in equation (1) is the sum of the pollution cost rates associated with system operation, $\dot{B}_{\text{prod}}$ the sum of the revenues generated by the products delivered, and $\dot{K}$ the sum of fixed cost rates (i.e. those costs independent of system synthesis, design and operation). Note that additional costs, such as augmented maintenance costs, augmented building costs, etc. could be added to the terms appearing in equation (1). They are not mentioned for the sake of simplicity.

The vector $\boldsymbol{x}$ above is the set of independent or decision variables (degrees of freedom) for the model while $\boldsymbol{y}$ contains the dependent variables. The equality constraints describe the mass and energy balances, which the system obeys as well as any component performance characteristics[3] 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 [14].

As mentioned above equation (1) may be expressed either in monetary or in physical units. Physical units would generally be expressed in units of exergy resulting in a so-called exergy life cycle analysis and optimization. Exergy is used since it accounts for both the quality and the quantity of energy used. In fact, every real thermodynamic process, which occurs within a system is associated with the loss of exergy. Thus, costs expressed in exergy units, may be defined as the exergy loss due to real processes occurring over the life cycle of, in our case, the DHN, i.e. the exergy losses associated with the DHN's processes of equipment manufacture and recycling as well as operation (including resource preparation and transport).

The pollution cost rate $\dot{C}_{\text{pol}}$ in equation (1) can be expressed as the sum of the pollution damage cost rates $\dot{C}_{\text{pol}_i}$ associated with the I substances i emitted during the operation of the DHN, i.e.

$$\dot{C}_{\text{pol}} = \sum_{i=1}^{I} \dot{C}_{\text{pol}_i} \tag{10}$$

where the synergistic effects of the different substances i are not taken into account because they add little to and may, in fact, detract from the overall system synthesis and design process [7, 8]. The pollution cost rate $\dot{C}_{\text{pol}_i}$ is expressed as a function of the pollution measure $\dot{p}_i$. A linear form for $\dot{C}_{\text{pol}_i}$ is assumed, namely

$$\dot{C}_{\text{pol}_i} = c_{\text{pol}_i} f_{p_i} \dot{p}_i \tag{11}$$

where:

- c_{pol_i} is the unit pollution damage cost due to the emitted substance i[4]. This cost may be expressed either in monetary or exergetic units. When expressed in exergetic units, c_{pol_i} represents the specific exergy associated with the emitted substance i[5] or which would be required if we wanted to reduce the emitted substances into harmless compounds (see [15]).
- f_{p_i} is the pollution penalty factor used to penalize the pollution costs and guide the synthesis and design of the system away from undesirable levels of emissions. This factor depends on the environmental pollution rate of substance i, on the existing pollutant level with respect to i and on limits set by society.
- $\dot{p}_i$ is the measure of pollution which represents the level of emission of i.

The use of f_{p_i} allows a nonlinear adjustment of the penalty associated with a particular pollutant, guiding the search for the optimal synthesis/design solution away from undesirable regions of the solution space and towards those more beneficial to the system's impact on the environment.

[3] Performance characteristics for off-design behavior are included in the synthesis/design process when time and, thus, operation are taken into account.

[4] Note that both c_{pol} or the product ($c_{\text{pol}} f_p$) could form the basis for a government tax or just a virtual tax used to allow a coherent ranking between technology alternatives and guide the attribution of subsidies.

[5] The link between exergetic terms and pollution damage is still an active research area and it is worth noting that the specific exergy of the emitted substance i may sometimes have little relationship with the real induced damage, in which case the second alternative mentioned above should be preferred.

The factor f_{p_i} is defined according to a set of rules, which account for the gravity of the emissions related to the energy system considered as well as on the existing conditions of pollution either local or global (so-called immissions). The basic idea is that it is not as damaging to emit a local pollutant like CO in the middle of a desert than it is in the middle of a major city. When it comes to global effects like global warming, the factor f_p can be adjusted to account for country targets of greenhouse gas emissions as will be shown later. The following is the set of rules, which govern this function:

1. f_{p_i} must be an increasing function of the environmental pollution rate of substance i and of its existing level in the environment.

2. No penalty must be set when there is no emission of substance i.

3. The value of f_{p_i} is set equal to 1 when the existing environment is "free" of any excess of substance i. Note that this does not imply that $\dot{C}_{\mathrm{pol}_i} = 0$, meaning that it might still be desirable to keep accounting for pollution costs following the principle of precaution, but without any need for aggravated penalties.

4. The value of f_{p_i} increases more rapidly when the value of the environmental pollution rate of substance i is greater that its critical value and approaches infinity when the environmental pollution rate becomes very large.

5. The value of f_{p_i} increases more rapidly when the value of the pollutant level of substance i exceeds its critical value.

6. The value of f_{p_i} increases with a decrease in the critical values of the environmental pollution rate and of the pollutant level of substance i.

A function that satisfies the above requirements is the inverse of the following function $P_i(\dot{\phi}_i)$, called the Pollution Function, proposed in [12] on the basis of works reported in [6–8]:

$$P_i(\dot{\phi}_i) = \left[1 + \frac{\dot{\phi}_i}{\dot{\phi}_{\mathrm{c}i}} \frac{\kappa_{0i}}{\kappa_{\mathrm{c}0i}} \exp\left(\frac{\dot{\phi}_i}{\dot{\phi}_{\mathrm{c}i}} \frac{\kappa_{0i}}{\kappa_{\mathrm{c}0i}}\right)\right]^{-1} \tag{12}$$

where $\dot{\phi}_i$ is called the environmental pollution rate, $\dot{\phi}_{\mathrm{c}i}$ represents its critical value, κ_{0i} its pollutant level and $\kappa_{\mathrm{c}0i}$ its critical pollutant level.

When the quantity of substance i is expressed as a concentration c_i (expressed for example in kg of i per Nm^3 of exhaust gases e) in the exhaust gases with a volumetric flow rate $\dot{V}_\mathrm{e}$, $\dot{\phi}_i$ is given by

$$\dot{\phi}_i = \frac{1}{V} s_i c_i \dot{V}_\mathrm{e} \tag{13}$$

where s_i is the specific entropy of emitted substance i and V is a control volume representative of the zone affected by the emissions considered.

The critical value $\dot{\phi}_{\mathrm{c}i}$ of the environmental pollution rate is given as a function of the critical values of the specific entropy and concentration in the exhaust gases (as defined by limits set by society [6, 7]):

$$\dot{\phi}_{\mathrm{c}i} = \frac{1}{V} s_{\mathrm{c}i} c_{\mathrm{c}i} \dot{V}_\mathrm{e} \tag{14}$$

The environmental pollution rate of substance i is defined by the increase due to the presence of substance i of the environmental volumetric entropy with respect to its natural (or pure) condition value. It is defined by

$$\kappa_{0i} = \frac{1}{V}(S_{0i} - S_{0i-\mathrm{nat}}) \tag{15}$$

This can also be written as

$$\kappa_{0i} = s_{0i} c_{0i} - s_{0i-\mathrm{nat}} c_{0i-\mathrm{nat}} \tag{16}$$

where c_{0i} represents the current concentration of substance i in the environment and $c_{0i-\mathrm{nat}}$ its concentration in a natural (or pure) state. s_{0i} and $s_{0i-\mathrm{nat}}$ represent, respectively, the current value of the specific entropy of substance i in the environment and its value in a natural (or pure) state. Concurrently, the critical value of the pollutant level is defined by

$$\kappa_{\mathrm{c}0i} = s_{\mathrm{c}0i} c_{\mathrm{c}0i} - s_{0i-\mathrm{nat}} c_{0i-\mathrm{nat}} \tag{17}$$

where $s_{\mathrm{c}0i}$ and $c_{\mathrm{c}0i}$ are the critical values of s_{0i} and c_{0i}.

Recently, a modification of equation (12) has been suggested as the pollution function [13] in order to improve its behavior for low emission rates. The new pollution function, noted Π_i, is defined as

$$\Pi_i(\dot{\phi}_i) = P_i(\dot{\phi}_i) + [1 - P_i(\dot{\phi}_i)] P_i(\dot{\phi}_i) \tag{18}$$

Figure 1 shows the behavior of Π_i as a function of the ratios $\dot{\phi}_i/\dot{\phi}_{\mathrm{c}i}$ and $\kappa_{0i}/\kappa_{\mathrm{c}0i}$. The pollution factor f_{p_i} is then defined by

$$f_{p_i} = \frac{1}{\Pi_i} \tag{19}$$

As can be seen from *figure 1*, the function Π_i provides an ideal S-shape function similar to the one conceptually introduced by Kummel [16]. It allows a coherent asymptotic approach at both ends of the domain of validity of the function tending towards one for negligible

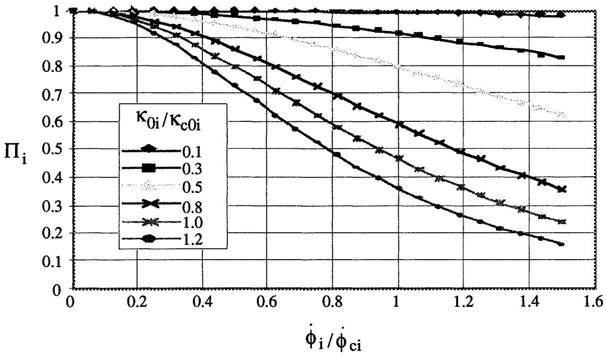

Figure 1. The pollution function as a function of the ratios of environmental pollution rates $\dot{\phi}_i/\dot{\phi}_{ci}$ and pollutant levels κ_{0i}/κ_{c0i}. According to equation (19), this function intervenes at the denominator with little influence when close to 1 and major effects when close to 0.

emissions and towards zero for excessively high emissions (f_{p_i} tending towards 1 or towards infinity).

The pollution measure $\dot{p}_i$ adopted here is the mass flow rate of emitted substance i, which is consistent with the monetary units for c_{pol_i} found in the literature [17] or with the physical units for specific exergy of emitted substance i. Thus,

$$\dot{p}_i = \dot{M}_i \quad (20)$$

Now returning to equation (8), both $\dot{C}_{\text{equip}}$ and $\dot{C}_{\text{pol\_equip}}$ must be defined in order to determine the augmented equipment cost rate $\dot{C}'_{\text{equip}}$. The former can be expressed for N pieces of equipment as

$$\dot{C}_{\text{equip}} = \frac{f_{\text{a}}}{3\,600 N_{\text{op}}} \sum_{n=1}^{N} (C_{\text{equip}})_n \quad (21)$$

where N_{op} is the number of operating hours during the economic lifetime of the DHN, and $(C_{\text{equip}})_n$ is the equipment cost (investment, etc.) associated with element n. When expressed in monetary units, the factor f_{a} is a nondimensional amortization factor defined as, for example, inversely proportional to the amortization period valid for the N elements. When the costs are expressed in exergetic units, f_{a} is also nondimensional and inversely proportional to the lifetime period of the N elements. Furthermore, in physical units, the equipment costs are proportional to the exergy losses, which occur during the processes mentioned above, starting from the point of resource extraction and ending with the removal of the equipment used by the energy system (e.g., a DHN). For this case, the sum of equipment costs is expressed as

$$\sum_{n=1}^{N} (C_{\text{equip}})_n = \sum_{n=1}^{N} (Ex_{\text{me}} + Ex_{\text{man}} + Ex_{\text{rem}} - Ex_{\text{mx}})_n \quad (22)$$

where:

Ex_{me} is the exergy associated with the material entering the energy conversion system;

Ex_{man} is the exergy associated with the manufacturing chain of processes which produces the equipment used by the energy conversion system;

Ex_{rem} is the exergy associated with the chain of processes which remove equipment used by the energy conversion system;

Ex_{mx} is the exergy associated with the material exiting the energy conversion system at the end of its useful lifetime.

Turning now to $\dot{C}_{\text{pol\_equip}}$, it may be expressed by

$$\dot{C}_{\text{pol\_equip}} = \sum_{n} \sum_{i} \sum_{\pi} c_{\text{pol}_{in\pi}} f_{p_{in\pi}} \dot{p}_{in\pi} \quad (23)$$

where:

$c_{\text{pol}_{in\pi}}$ is the unit pollution damage cost due to substance i emitted during the process π associated with equipment n. This cost may be expressed in either monetary or exergetic units.

$f_{p_{in\pi}}$ is the pollution penalty factor associated with substance i of process π and equipment n.

$\dot{p}_{in\pi}$ is the measure of pollution for substance i of process π and equipment n.

In order to determine the augmented resource cost rate $\dot{C}'_{\text{res}}$ in equation (9), both $\dot{C}_{\text{res}}$ and $\dot{C}_{\text{pol\_res}}$ must be defined. The former is expressed by the product between the specific or unit cost c_{res} of resource r and its rate of utilization, $\dot{y}_{\text{res}}$:

$$\dot{C}_{\text{res}} = \sum_{r=1}^{R} \left(c_{\text{res}} \dot{y}_{\text{res}}\right)_r \quad (24)$$

The specific cost c_{res} may be expressed either in monetary units (the market price) or in exergetic units. If the latter, c_{res} is defined as

$$c_{\text{res}} = ex_{\text{pt}} + ex_{\text{res\_in}} - ex_{\text{res\_out}} \quad (25)$$

where ex_{pt} is proportional to the specific exergy loss associated with resource preparation and the transport chain of processes, $ex_{\text{res\_in}}$ is the specific exergy associated with the resource entering the system and $ex_{\text{res\_out}}$ the specific exergy associated with the resource leaving the system (e.g., after combustion, $ex_{\text{res\_out}}$ is associated with the combustion gases).

Completing the definition of the augmented resource costs is the term $\dot{C}_{\text{pol\_res}}$, which may be expressed by

$$\dot{C}_{\text{pol\_res}} = \sum_r \sum_i \sum_\pi c_{\text{pol}_{ir\pi}} f_{p_{ir\pi}} \dot{p}_{ir\pi} \qquad (26)$$

where:

$c_{\text{pol}_{ir\pi}}$ is the unit pollution damage cost due to substance i emitted during the process π associated with resource r. This cost may be expressed either in monetary or exergetic units.

$f_{p_{ir\pi}}$ is the pollution penalty factor associated with substance i of process π and resource r.

$\dot{p}_{ir\pi}$ is the measure of pollution for substance i of process π and resource r.

Finally, the sum of revenues $\dot{B}_{\text{prod}}$ in equation (1) results from the sale of services/products by the system. In the case of a DHN with cogeneration, these are heat and electricity. In monetary units, this may be formulated by

$$\dot{B}_{\text{prod}} = \sum_{uQ} b_{uQ} \dot{M}_{uQ} \Delta h_{uQ} + \sum_{uE} b_{uE} \dot{E}_{uE} \qquad (27)$$

where $\dot{M}_{uQ}$ is the mass flow rate of the local network water, Δh_{uQ} is the difference between the specific enthalpy of the water provided to user uQ and the water returned from this same user. b_{uQ} is the unit price of heat, and $\dot{E}_{uE}$ is the electric power sold to the user uE at a unit price of b_{uE}. In exergy units, $\dot{B}_{\text{prod}}$ is written as

$$\dot{B}_{\text{prod}} = \sum_{uQ} \dot{M}_{uQ} \Delta(h_{uQ} - T_0 s_{uQ}) + \sum_{uE} \dot{E}_{uE} \qquad (28)$$

where T_0 is the temperature of the environment and s_{uQ} the specific entropy of the local network water. The difference is calculated again between supply and return of the user uQ's local heating circuit. Note, that in exergetic units the value of the exergy associated with the delivered electricity corresponds to its energy value (e.g., the unit price for exergy is equal to 1 for electricity).

The formulation outlined above is applied to the super-configuration of the district-heating network shown in the figures below. This super-configuration is composed of a number of different elements, all potentially at the disposal of the design engineer for optimally meeting the heating demand of a given set of DHN users. A brief discussion of the development and nature of the super-configuration is given in the following section.

3. ENVIRONOMIC MODEL: THE SUPER-CONFIGURATION

Based on the above formulation, the synthesis (choice of system configuration) aspect of the environomic model is represented by what is called a super-configuration. This is a complete set of system components that potentially and realistically[6] could be part of the final optimal DHN configuration which best meets the demands required by the users. The presence of a particular piece of equipment in a given configuration (i.e. super-configuration subset) at any point during the search for the optimum configuration depends on the values taken by the independent variables that correspond to the synthesis part of the optimization. The final set of values for these independent variables as well as those for design and operation are those, which minimize the costs represented by equation (1).

A general schematic of the DHN super-configuration model is shown in *figure 2*. It includes a central plant, the main distribution network, and the users connected to this network. The model accounts for the preparation chain of processes, which provide the fuel and electricity used by the system, starting from the primary energy resource and ending with delivery of the fuel and electricity to the system (in this case the central plant of the DHN). The system's network delivers energy to meet the users' heating loads during the heating season and domestic hot water throughout the year. The central plant super-configuration includes one heat pump (HP_cen), one cogeneration gas reciprocating engine unit (GE), one gas turbine cogeneration unit (GT) and one gas furnace (GF). The heat pump works between the heat source (river, lake, etc.) and the main distribution network. Its compressor is driven by an electric motor with the electricity taken either from the utility grid or generated by the central plant itself employing one or more cogeneration units. These cogeneration units provide additional heat to the main distribution network thanks to the engine's water and lubrication oil cooling circuits as well as the heat

[6] "Realistically" is used here in the sense of an expert (e.g., the design engineer) making a predetermination of what combinations of components could realistically make-up a system, which responds adequately to the demands of the users. Thus, unnecessary or nonrealistic combinations are eliminated a priori in order to reduce the size of the optimization problem, which even in reduced form is formidable.

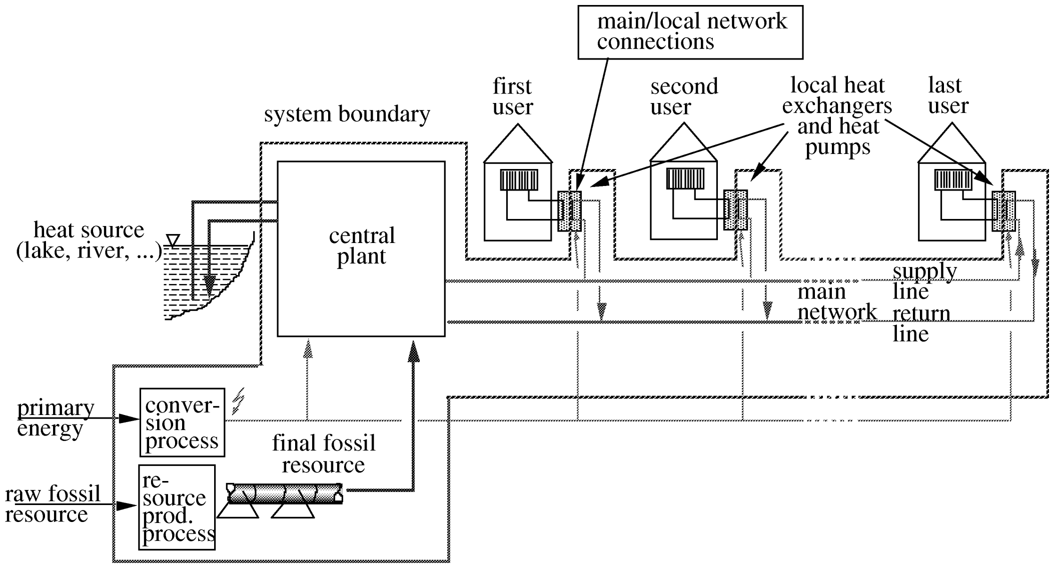

Figure 2. A general schematic of the DHN system modeled.

recuperated from the engine's and/or turbine's exhaust gases. A furnace is also present in the super-configuration 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, satisfies the lower temperature range of the network heating. This heat may be supplemented by the heat provided by the cogeneration unit(s) and the furnace (i.e. the heat pumps are inserted upstream of these other units). The schematic for the super-configuration of the central plant of the DHN appears in *figure 3*. *Figure 4* shows the super-configuration for each user, which includes a heat exchanger working between the main network supply line and the local heating network (SL_HX), a heat pump working between the main network supply line and the local heating network (SL_HP), a heat exchanger working between the main network return line and the local heating network (RL_HX), a heat pump working between the main network return line and the local heating network (RL_HP), two heat exchangers for domestic hot water heating (HDW_HX1 and HDW_HX1) and a supplementary electrical heater for domestic hot water heating (HDW_Aux). Note that the super-configuration of the last user does not include the possibility of introducing a heat exchanger or a heat pump on the return line.

Each user super-configuration, thus, provides a number of options for transferring heat between the main distribution network and the local building or user network, including options for domestic hot water preheating and heating. The connection elements work in competition with one another. Due to typical heating temperatures, the water coming from the supply line heat pump and heat exchanger is in general warm enough to at least preheat the cold water before returning to the central plant. Domestic hot water is produced through heat exchange with the supply line water and/or by an electrical heater. The interest in having an electrical heater option is that it is not necessary for the DHN water temperature to be warm enough to produce domestic hot water by heat exchange alone.

Of course, both the users and central plant super-configurations described above are 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 super-configuration can or necessarily should be totally inclusive 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, the more difficult it is to find the global or a set of near-global optimum solutions since the types of models considered are typically highly nonlinear, noncontiguous and involve a large number of degrees of freedom.

Finally, a complete set of results for the subset of this DHN super-configuration that most optimally meets the users' demand is presented in Part II [1]. For additional

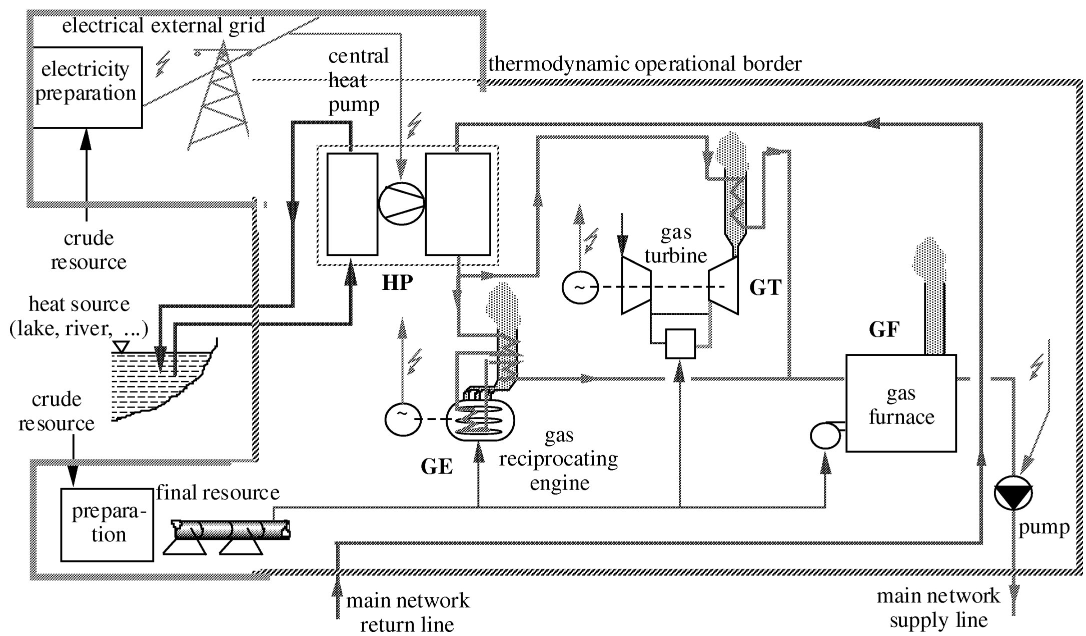

Figure 3. Central plant super-configuration schematic for the DHN system.

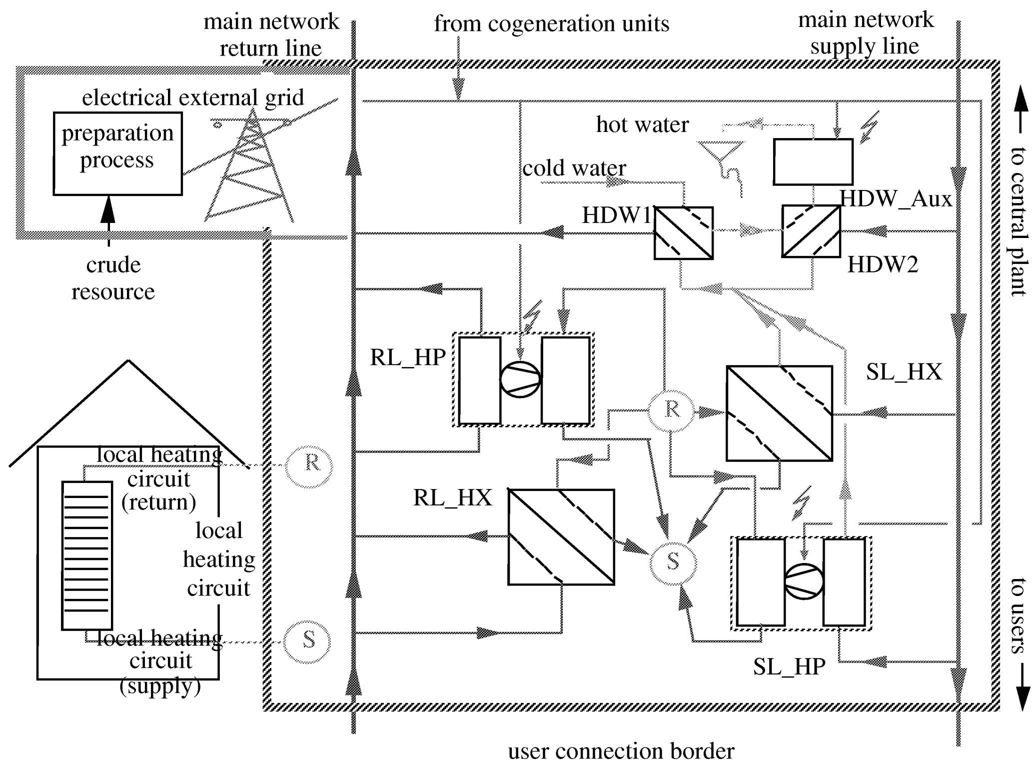

Figure 4. User connection super-configuration schematic for the DHN system.

details on the method and on model development, the reader is referred to [12].

4. CONCLUSIONS

Steps towards the design of sustainable energy systems must include tools for simultaneously considering the broad range of parameters linked to the thermodynamic, economic and environmental aspects of a system. The environomic approach proposed relies on a formulation of the synthesis and design problem in a way, which makes it amenable to the use of powerful algorithms (e.g., genetic algorithms) able to solve MINLP (mixed integer nonlinear programming) problems. A general formulation for modeling a DHN system (or any other energy conversion system) has been presented here. The specific formulation and the results derived from its optimization appear in the accompanying article [1]. Future steps include a truly time-dependent optimization of the operational sequences as well as an extension of the model to satisfy a cooling demand with for example a four-pipe network (one pair for heating and one pair for cooling).

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