MULTI-CRITERIA OPTIMIZATION OF A HEAT PUMP BASED DISTRICT HEATING SYSTEM IN THE CITY OF BEIJING

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ABSTRACT

A more widespread usage of heat pumps would contribute to significantly reduce both local and global environmental impacts. This is particularly relevant within cities, where advanced integrated energy systems incorporating heat pumps and associated with district heating networks offer interesting opportunities for CO_2 emissions abatement.

Planning for medium or long term investments in an unsettled economic and regulatory environment in particular with regards to global environmental issues and accounting for the technical evolution requires the ability to deal with a large number of parameters. This paper illustrates through the case study of a district heating in the city of Beijing the ongoing efforts towards multi-criteria optimization of advanced energy systems in order to provide decision makers with a coherent technology assessment methodology.

A superstructure including both centralized and decentralized heat pumps and cogeneration units associated with a district heating network is considered for the heat supply of two urban areas, respectively residential and commercial buildings. A simultaneous consideration of thermodynamic, economic and environmental criteria is used to identify the most interesting alternatives in the Chinese context.

The results of the optimization process, obtained in the form of Pareto frontiers, reveal their economic and environmental performances, as well as deliver valuable information on their absolute and marginal cost of CO_2 emissions reduction. This information allows to define the tax level or the emissions permit price required to induce enough economic incentive for their implementation.

1. INTRODUCTION

China's total energy production and consumption grew rapidly with an average annual increase rate of 3.2 % and 4.3 % respectively from 1980 to 1999, mainly relying on coal [China State Statistics Bureau, 1999]. Energy-related emissions are projected to represent 28 % of the world CO_2 emissions increase, which would make China the world's largest CO_2 emitter after 2020, surpassing the United States. A break down of energy use in China shows that almost two thirds of its primary energy is end-used in the form of thermal energy, with a very large proportion at low temperature (domestic water and air-heating of residential and commercial buildings). Moreover, the emissions associated with heat supplied to the building sector is one of the main sources of air pollution in cities.

While high population density is a main cause of air and water pollution, it nevertheless provides the opportunity to reduce per-capita energy consumption through the introduction of integrated energy systems based on cogeneration units associated with heating or cooling networks. An additional step towards even more efficient systems can be achieved when including heat pumps into such systems [Calm, 1980], [Lorentzen, 1990], [Curti, 2000]. Recovering heat from the environment, heat pumps allow much higher heating supply first law efficiencies than conventional systems.

In this paper, a case study has been undertaken which considers an integrated energy system superstructure including both centralized and decentralized heat pumps and cogeneration units associated to a district heating network for the heat supply of two urban areas, respectively residential and commercial buildings, in the city of Beijing.

The results of the multi-criteria optimization based on the modeling developed for this type of energy conversion system provides valuable information on their economic and environmental performances in the Chinese context, and also on the *minimal* incremental cost required to reduce the annual emissions rate by an incremental emission unit. When such a cost, commonly referred to as marginal cost, is higher than an eventual tax level adopted by the regulator, or than the price on the market of emission permits if such an emissions trading scheme has been implemented, there is no more incentive to reduce further internally the emissions rate. The knowledge of this information defines therefore the optimal design and operation of a given energy conversion system in a specific context.

2. THERMO-ECONOMIC MODELING AND OPTIMIZATION OF THE PROPOSED ADVANCED DISTRICT HEATING ENERGY SYSTEM

The case study considers two clusters of respectively residential and office buildings to be built in Beijing, their main characteristics being given in table 1. The two building areas, including small local heating distribution networks, are located along a primary linear district heating network supplied by a decentralized energy conversion plant. The residential and the office building areas are respectively distant by 4 Km and 1 Km from the plant.

The superstructure of the energy conversion plant is given in figure 1. The water of the return line enters the condenser of a two stage heat pump, which recovers heat from a large capacity cold source materialized by a canal. The water mass-flow is then driven to the heat exchangers of respectively a gas turbine cogeneration unit, and/or a gas engine cogeneration unit, if those units are chosen to be introduced. An additional boiler completes the heating load in order to achieve the required supply temperature of the district network. Gas turbine, gas engine and auxiliary boiler are natural gas fired (LHV of 43.96 MJ/Kg). Physical parametric modeling of each one of these elements has been integrated into the overall modeling structure.

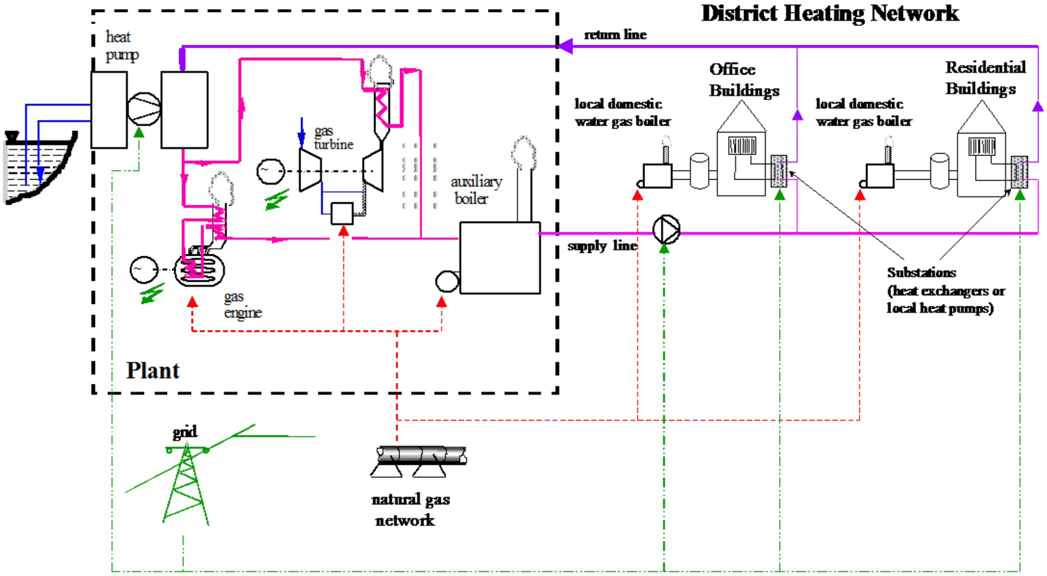


Figure 1: Superstructure of the energy conversion plant supplying the office and residential building areas through the district heating network.

The main district network can supply the two local substations either through heat exchangers or through local heat pumps, or through a combination of both alternatives, with in addition the choice of a connection on the supply line or on the return line. The choice of local heat pumps allows a reduction of the supply temperature of the network since the temperature is locally upgraded to the level required by a specific type of users. The option of a connection through a local heat pump on the return line presents the advantage of a higher efficiency for the plant's heat pump, since it reduces the difference of temperature between the cold and hot sources. Regarding domestic hot water, separated networks are considered and choice is given between deriving part of the district heating mass-flow to heat exchangers, or using local gas boilers, or a combination of both alternatives. In winter, the water leaving the supply line heat exchanger for space heating or the evaporator of a local heat pump can also be used for domestic water preheating.
Details on the physical modeling of each specific component described above can be found in [Curti, 2000].

Table 1: Characteristics of the two building areas considered.

	Space Heating Duration Time [days]	Floor Area [10^3 m^2]	Minimum Temp. Required in Winter [°C]	Heating Load [MW]	
				Space Heating	Domestic Hot Water
Office building	150	460	65	27.6	1.4
Residential building	150	136	80	6.8	1.0

The year is divided into a heating season which requires space heating, period of about 150 days on average in Beijing, and the rest of the year[1]. Daily fluctuations of the heating demand are considered to be managed by the network storage capacity and the system is therefore designed for seasonal average loads. The rest of the year, heat is only required for domestic hot water purposes. *The purpose of the energy conversion system to be installed is the heating supply of the two building areas. The integrated energy system is therefore designed for the winter conditions and if cogeneration units are introduced, their power production is only dedicated to internal needs, i.e. central heat pump, network pumps, local heat pumps*. Their maximal capacity is therefore constrained by a power output which has to match internal requirements. It can be however decided to import all or part of the required power from the grid.
For a chosen winter supply temperature, and considering the choice of the configuration at the users, their heating demands and their required level of temperature, the returning temperature and the network mass-flow can be derived. The natural gas boiler insures that the heat balance is respected, complementing the heat supplied by the heat pump and the heat recovered from the cogeneration units.

Once designed for winter conditions, the plant still has to supply heat during the rest of the year for domestic water requirements. Since power exportation is not considered here, cogeneration units have been imposed 1) to be shut down when no space heating is required if the configuration selected includes a central heat pump[2], and 2) to run at nominal load throughout the year, with the exception of maintenance periods, if no central heat pump is considered. In the latter situation, the optimal capacity for cogeneration should therefore converge to the summer internal power requirements, i.e. the network pumps operation.
During this period, the minimum required temperature is the one fixed for the domestic hot water, i.e. 65 °C. Choice is therefore given to reduce the temperature relative to winter conditions. Likewise the winter supply temperature of the heating network, the supply temperature during summer is also considered as a decision variable to be optimized. Lower supply temperature increases the coefficient of performance of the central heat pump but heat transfer is affected at the user's side. Higher water mass-flow in the district or larger local gas boilers capacity are then necessary. As previously

[1] Beijing does not experience a significant mid-season.
[2] This rule allows the choice of a cogeneration unit capacity large enough for driving the heat pump in winter while avoiding operation at penalizing part-load in summer which shows excessively lower requirements, power is then imported from the grid when the heat pump does not operate at all or only at very partial load in summer.

mentioned, the system is designed for winter conditions, including the domestic hot water heat exchangers. Off-design temperature profiles of these components are derived with as the main assumption a same mass-flow as in winter (the hot water demand can be assumed constant along the year), and therefore a similar heat transfer efficiency if one considers that the part load performance is essentially a function of the ratio of respectively nominal and part load mass-flows.

Evolutionary algorithms have proven to be robust and effective for the resolution of non-linear, non-continuous, and mix real integer problems such as those encountered when dealing with integrated energy systems. Until recently, modeling and optimization of integrated energy systems regarding technical, economic and environmental issues have been undertaken at the Laboratory of Industrial Energy Systems (LENI), Swiss Federal Institute of Technology, Lausanne, using genetic algorithms for the resolution of the so-called *environomic* formulation, which includes all criteria within a single objective aggregated function [Olsommer, *et al*., 1999], [Pelster, *et al*., 2000], [Curti, *et al*., 2000], [Burer, *et al.*, 2000]. This formulation allows a minimization of the overall internalized cost of an energy system, accounting for design, installation, operation but also pollution through the introduction of pollution cost factors. However, given the difficulty encountered sometimes when trying to express certain criteria in financial terms, a multi-criteria optimization may be preferred. Such an approach is currently in development at LENI with the recent development of a new clustering evolutionary multi-objective optimizer. This new evolutionary algorithm allows multi-criteria optimization but also can retain if desired several local Pareto-optimal frontiers, rather than only the global frontier. In such a case, it does not drive to a single optimum curve but allows the identification of multiple solutions considered as performant but different. This property is obtained through a clustering technique which ensures that competition between individuals is local in variable space [Leyland, Molyneaux, Favrat, 2001].

The table 2 presents the decision variables of the optimization problem with their respective boundaries. In this problem, all variables are chosen to be of real type. However, when as an example a value for the gas engine fuel mass-flow is chosen by the optimizer between zero and a value under which a gas engine is not practically rational, it represents a discontinuity in the overall system since the gas engine is not selected and the configuration changes drastically. The same can be noticed for other components. As another example, in practice a maximum temperature is defined at the exit of a heat pump compressor for the lubricant not to be altered. Whenever the conditions are such that this constraint is not respected, the heat pump is not selected which induces again a discontinuity.

In this study, two objectives are simultaneously optimized: the *annual total cost of energy conversion* and the *annual CO_2 emissions rate*. Pareto-optimal frontiers are therefore derived, which define for a given technology, within its feasible domain, the minimum cost required for achieving any level of CO_2 emissions, or inversely the maximum CO_2 emissions abatement achievable for a given financial effort.

The annual total cost of energy conversion is given by the sum of the annual capital cost and the annual operating cost. The annual capital cost is a function of 1) the total investment cost, 2) the interest rate (6% in this case), and 3) the chosen period for the

total capital cost amortization[3]. The operating cost is composed of the natural gas consumption and power importation from the grid. In the context of Beijing, the natural gas and electricity prices are respectively taken as 2 [cts/KWh] and 6 [cts/KWh].
The annual CO_2 emissions rate is the sum of the emissions associated with each component introduced and therefore derives from the physical modeling. The emissions associated with power importation from the grid considers the Beijing average emissions rate of 1 [Kg CO_2/KWh].

<u>Table 2 : Decision variables and their lower and upper boundaries.</u>

Decision variables	**unit**	**lower bound**	**upper bound**
Plant			
Heat Pump Nominal Power	MWth	0.0	40.0
Gas Engine Fuel Mass-flow	kg/sec	0.0	2.0
Gas Turbine Fuel Mass-flow	kg/sec	0.0	2.0
Gas Engine Water Mass-flow Share	-	0.0	1.0
Winter Supply Temperature	K	308.15	368.15
Heat Pump Part Load Fraction	-	0.0	1.0
Summer Supply Temperature	K	308.15	368.15
Office Buildings Area			
Local Heat Pump Supply Line Share	-	0.0	1.0
Local Heat Pump Return Line Share	-	0.0	1.0
Heat Exchanger Supply Line Share	-	0.0	1.0
Dom. Hot Water Derived Mass-flow	kg/s	5.0	10.0
Pinch Heat Exchanger Supply Line	K	2.0	15.0
Pinch Heat Exchanger Returne Line	K	2.0	15.0
Residential Buildings Area			
Local Heat Pump Supply Line Share	-	0.0	1.0
Heat Exchanger Supply Line Share	-	0.0	1.0
Dom. Hot Water Derived Mass-flow	kg/s	10.0	30.0
Pinch Heat Exchanger Supply Line	K	2.0	15.0

3. RESULTS AND DISCUSSION

Figure 3 shows two sets of Pareto curves that were obtained, with respectively a 15 year period and a 5 year period for capital cost amortization (payback of investors and payment of interest). These sets are composed of separate clusters corresponding to different configurations which emerged from the multi-criteria optimization process. Within a cluster, the annual incremental cost required for progressively reducing the annual CO_2 emissions rate shows a smooth and continuous increasing evolution[4]. This is the result of variations of continuous design and operation variables. But jumps from a given cluster into another cluster require structural changes, i.e. changes of configuration

[3] This period corresponds to the number of years allocated by the investors for their full reumbersment and the payment of interests.
[4] The shape of a cluster can either be concave or convex. This first case corresponds to a marginal cost that increases with higher abatement rates ; it is a stable evolution, the optimal position within a cluster being reached when the marginal cost equalizes the tax level or the permit price. A convex shape is unstable : the marginal cost decreases with higher abatement rates. In such a case, either the marginal cost at the left extremity of the cluster is higher than the tax level and this extremity corresponds to the optimal position, or the marginal cost is lower, and in this case, the position shift all the way to the right extremity, only other stable position.

which induce discontinuities along the optimal frontier. Incremental costs – marginal costs – can only be defined within the clusters.
The optimal frontier for the 5 years capital cost amortization period shows 5 successive clusters, all 5 located on the optimal frontier and therefore defining the global optimum of the optimization problem. For the given system and context considered and for a given annual total cost, it is not possible to find a solution that releases less CO_2 in the atmosphere than the one corresponding to this curve. Respectively, for a chosen environmental target expressed in the form of a level of annual CO_2 emissions rate, there is no chance to spend less than the annual cost given by this curve. This is true all along the feasible domain of the system considered. The figure 4 gives for all individuals pointed by an arrow in figure 3 the share of each component in the investment cost and therefore allows the structural identification of the clusters.

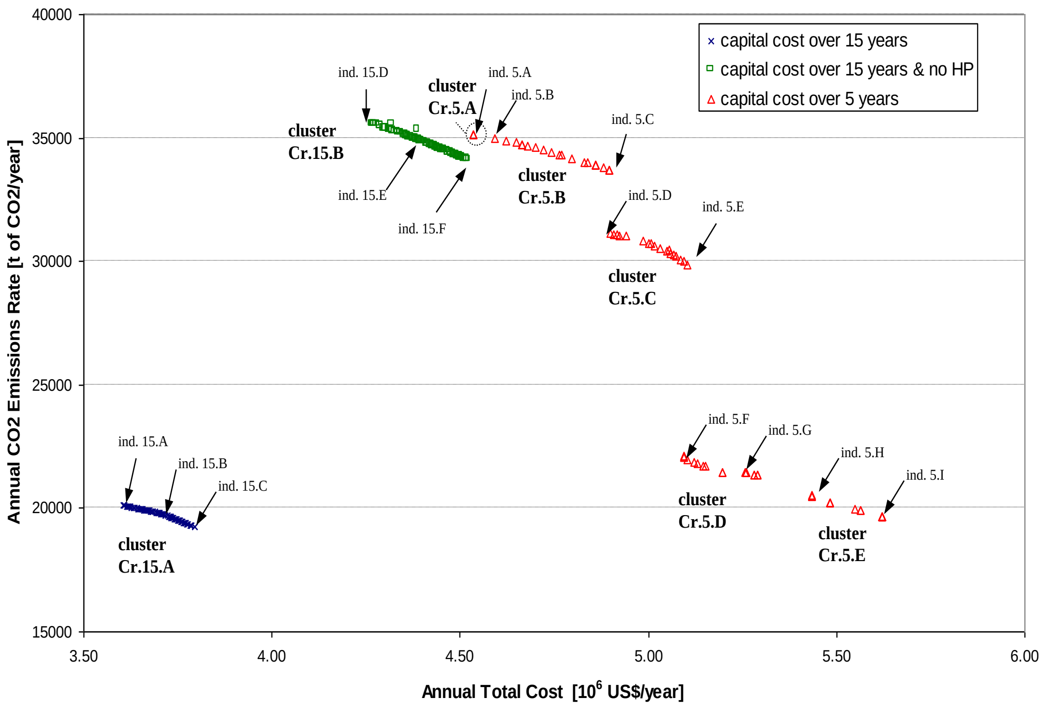


Figure 3: Results of multi-criteria optimization processes with the capital cost amortization period as a sensitivity parameter.

The cluster Cr.5.A which corresponds to highest emission rates and lowest costs appears to be a configuration based on a high capacity natural gas fired boiler supplying all the heat required during the space heating period (see figure 5). All the power required for network pumps is imported from the grid. The cluster Cr.5.B, starting with individual 5.B and ending with the individual 5.C defines a configuration based on a gas engine cogeneration unit and a gas boiler. A small size heat pump (up to 2.5 MWth) appears to be selected in the cluster Cr.5.C, driven by the gas engine which produces all the internal power requirements and supplies part of the heat. The size of the heat pump and of the gas engine increase together along the cluster, with a continuous decrease of CO_2 emissions and increase of investment cost (see figure 5 and 6). An additional boiler is still required. The cluster Cr.5.D is based on the same components but with a much larger capacity heat pump of 15 MWth. Finally, the cluster Cr.5.E opts for a heat pump capacity of 22 MWth driven by a gas turbine cogeneration unit. There is no more need for an additional boiler. The selection of a gas engine instead of a gas turbine in previous clusters is due to the fact that the gas engine is characterized by a much higher efficiency which makes it more economical than a gas turbine at medium power capacity. All these clusters have a similar configuration at the users with heat exchangers connected on the supply line and network supply temperatures of respectively 95 to 88 °C during the space heating period and 95 to 40 °C the rest of the year.

Each of both extremities of a cluster may either correspond to 1) a limit of the feasible domain for the technology considered (activation of a constraint) or 2) a break-even point, i.e. a point where an incremental variation of a continuous variable is still possible and would still bring to a better solution, but where an even better solution is obtained for the same cost with another configuration, which induces the jump down to another cluster. Regarding the 5 years capital cost amortization Pareto curve, individuals 5.A or 5.I are typical of the first case (constraint) with respectively no cheaper solution possible and no lower emissions rate achievable whatever the investment while respecting the constraints of the problem. Individuals 5.C or 5.E are examples of the second case (break-even).

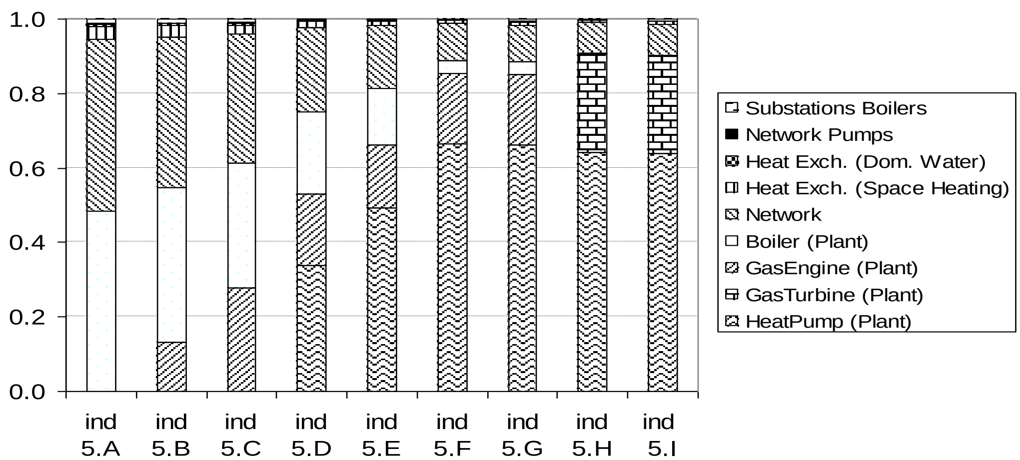
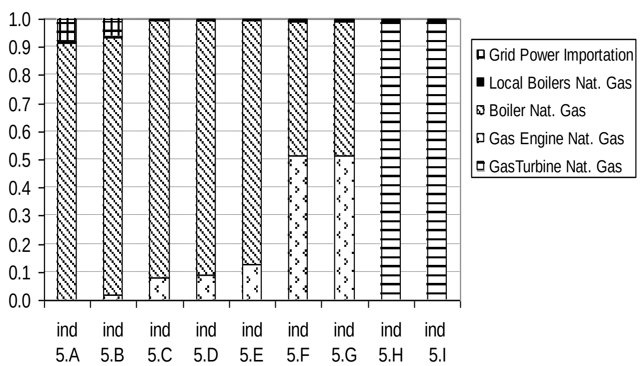


Figure 4: Share of each component in the total investment cost for selected individuals of the Pareto curve obtained for the case of a 5 year capital cost amortization period.



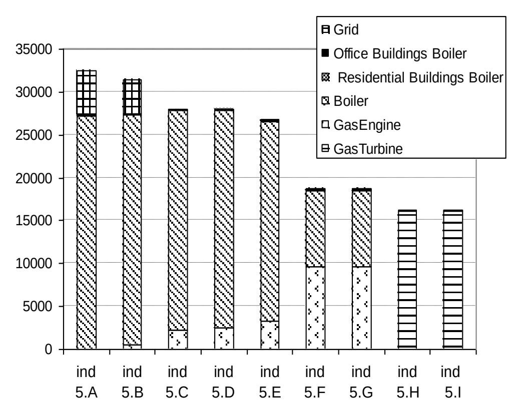


Figure 5: Share of each component in the operating cost (left side) and CO_2 emissions rate in [tons of CO_2 / year] (right side) during the space heating period.

Figure 6 shows the evolution of the total investment cost and of the annual operating cost along the Pareto curve, as well as the evolution of the global system efficiency[5] during the space heating period and the rest of the year. It can be seen that CO_2 emissions reduction is obtained in this situation by investing in more and more costly but more and more efficient systems in winter[6]. This higher efficiency, up to 1.45, has also an impact on the annual operating cost but since investment cost is given an important weight due to the short period chosen here for the capital cost amortization, this effect is not dominant.

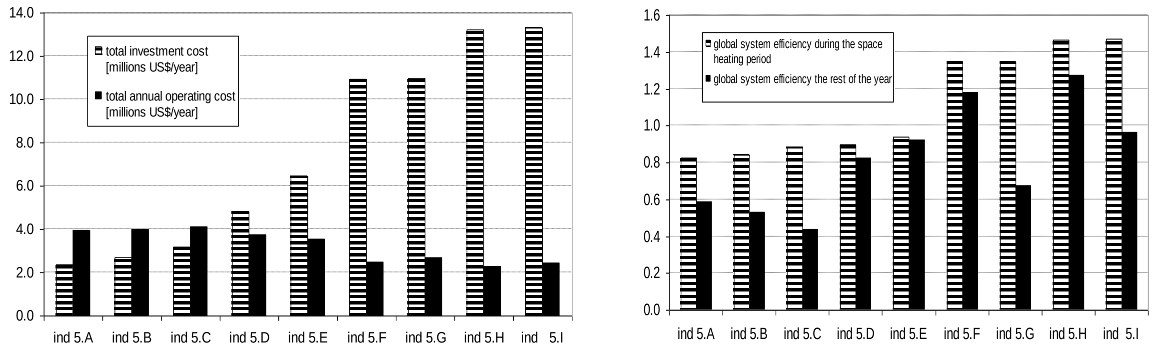


Figure 6: Evolution of the total investment cost, the total annual operating cost, the global efficiencies during the space heating period and the rest of the year along the Pareto curve for the case of a 5 years capital cost amortization's period.

Figure 7 gives the evolution of the total specific investment cost, defined by the ratio between total investment cost and total heating capacity of the system, as well as the evolution of the specific total annual heating cost, which corresponds to the price at which the heat should be sold for a economically viable operation of the energy conversion plant. The latter takes values from about 9 [US$/GJth] for the cheapest but most emitting system optimal configuration, up to 11 [US$/GJth] for the less emitting optimal configuration.

[5] The global system efficiency calculation takes into account the average efficiency at which the power eventually imported from the grid has been produced. Since in this specific case no power exportation is allowed, the efficiency is given by the ratio between respectively the heating supply and the sum of the energy brought by the natural gas consumed (based on the low heating value) and the power eventually imported.

[6] The global efficiency over the rest of the year is not of much significant importance due to a much lower demand.

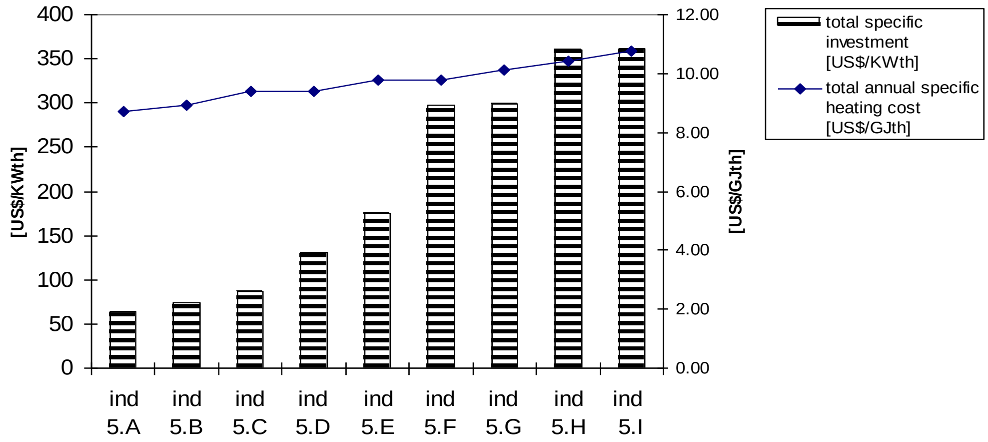


Figure 7: Evolution of the total specific investment cost and of the specific total annual heating cost along the Pareto curve for the case of a 5 year capital cost amortization's period.

The optimal frontier obtained for the 15 year capital cost amortization period is limited to the single cluster Cr.15.A. The selected configuration is similar to the cluster CR.5.E with a large capacity heat pump (22 MWth) and a gas turbine cogeneration unit. The second cluster Cr.15.B is not located on the global optimal frontier of the optimization problem. It was however retained by the optimizer as a local optimum corresponding to a configuration without a heat pump. As can be seen in figure 3, in such a case, the introduction of a heat pump in the system allows to almost divide by 2 the annual emissions rate while reducing at the same time the total annual cost by about 500'000 US$. The design of individuals 15.A to 15.C does not see structural changes. The slight reduction of the annual emissions rate is not obtained by an increased efficiency, but by decreasing the summer heat pump operating rate. As explained earlier, the gas turbine is shut down during this period, and the heat pump has to be driven through power importation from the grid, which is highly CO_2 intensive in Beijing. When reducing the operation of the heat pump in summer, power importation reduces and is compensated by a larger size of local natural gas boilers for complementing domestic water requirements. The situation corresponds therefore to fuel switching displacing coal used in large capacity power plants by natural gas used in local boilers operation. While the supply temperature of the network is around 90 °C for all individuals during the space heating period, it decreases the rest of the year from 90 °C for the individual 15.A to 35 °C for the individual 15.C. All configurations selected heat exchangers on the supply line for the connection of the users.

When a period of 15 years is accepted by investors for their reimbursement and the payment of interest, the configuration including a large heat pump and a gas turbine cogeneration unit is the most economical even when no pollution cost internalization is introduced. The cheaper solution obtained is about 14% less costly than the configuration with a boiler as the only component. However, such a long amortization period can be seen in itself as a way to subsidize more efficient technologies.

Coming back to the case of an amortization period of 5 years which would correspond more to private investors, figure 8 gives in relative values the annual total cost for any percentage of CO_2 emissions abatement referenced to a "business as usual" case chosen to be the individual 5.A. New environmental regulation in Beijing imposes the use of natural gas fired boilers instead of coal fired ones in new installations for SO_2 atmospheric pollution mitigation. As seen above, the configuration presented by the individual 5.A is precisely a large natural gas fired boiler, which makes it a good "business as usual" reference. The latter is located at the origin of the graph. As an example, it can be seen on this graph that reducing the CO_2 emissions rate by 38% would require the option of a different configuration (introduction of a heat pump driven by a gas engine cogeneration unit) and would increase the annual total cost of heat generation by about 15%. It can be also seen that the maximum abatement rate achievable through the introduction of a heat pump in replacement of a natural gas boiler is 45 % at a 25% higher total cost.
Finally, figure 9 illustrates the impact of a CO_2 tax, or of a given permit price on the market within an emissions trading scheme, on the design and operation of the energy conversion system considered. It gives the internalized total annual cost as a function of the annual emissions rate with the level of pollution internalization as a parameter. It reveals that a value of about 45 [US$/ton of CO_2] is required in order to give enough economic incentive for heat pump based configurations to be adopted when such a short period of capital cost amortization is required by investors. This value is high compared to figures expected in the next several years for certified emission reduction units within the framework of the Clean Development Mechanism. However, the price will rise with years as demand for emissions permit will grow when approaching the commitment period. Moreover, as demonstrated above, the value obtained is strongly dependent on the duration chosen for the capital cost amortization period[7]. Details rules and guidelines for a transparent implementation of CDM still need to be defined by the comity which has been established at COP7.

[7] or for the discounting rate, the level of which representing also a measure of the risk.

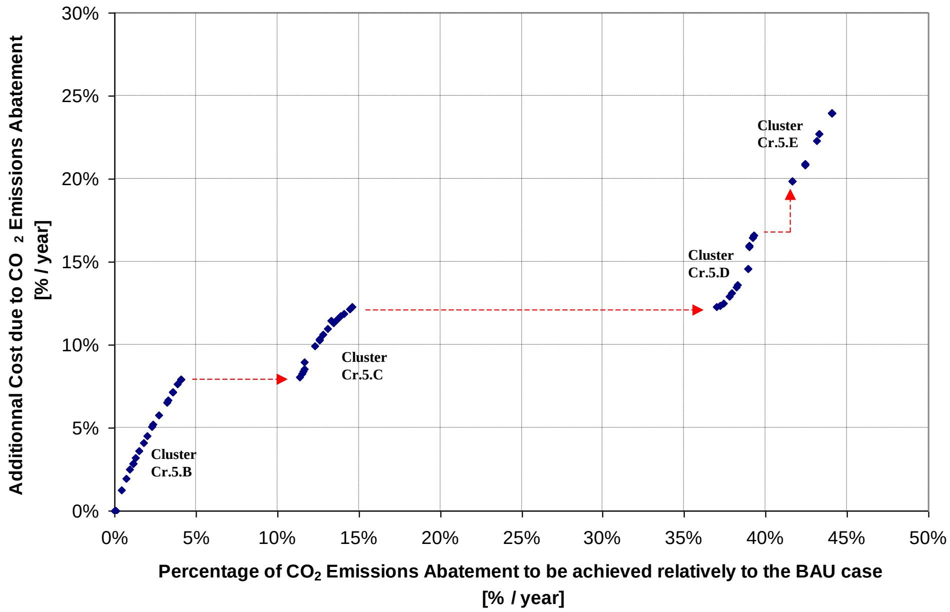


Figure 8: Additional annual total cost for any given percentage of CO_2 emissions abatement to be achieved relative to the "business as usual" case chosen to be the individual 5.A.

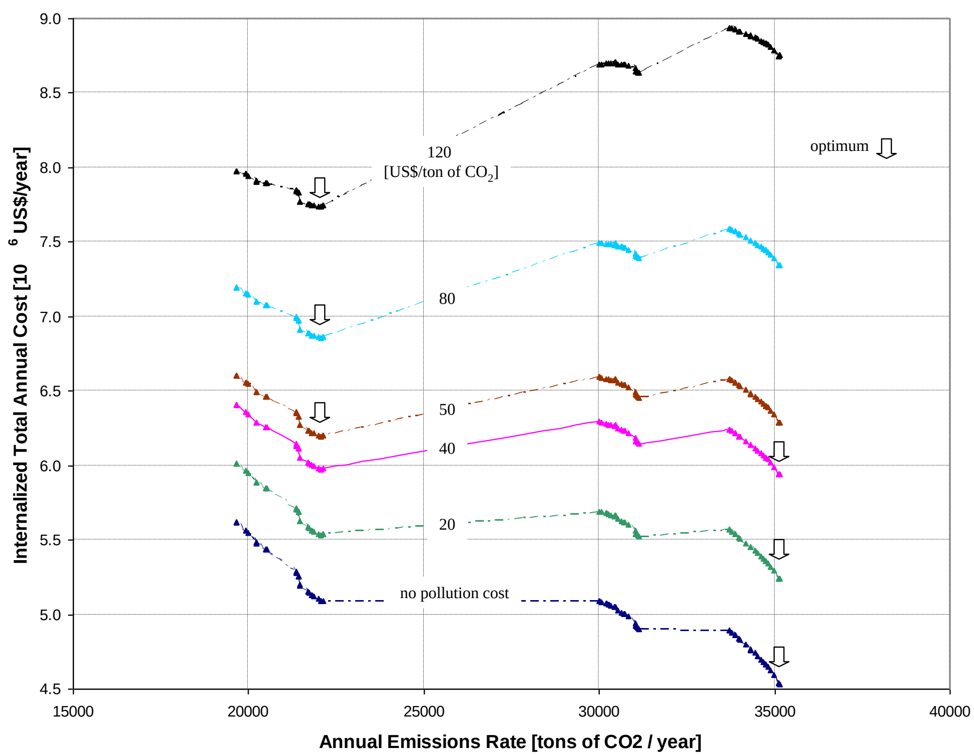


Figure 9: Internalized total annual cost of energy conversion as a function of the annual CO_2 emissions rate with as parameter the level of a CO_2 tax or the price of a permit on an emissions trading market.

4. CONCLUSION

This paper illustrates, through the case study of a medium scale district heating system in the city of Beijing, the high potential offered by the association of heat pumps and cogeneration units for CO_2 emissions abatement. Such integrated energy systems are called to play a major role in the future for the emergence of more sustainable urban areas. A multi-criteria optimization approach has been demonstrated to be of high interest, delivering with a similar computation time a substantial additional amount of information compared to mono-criteria approaches. An information of particular relevance is the marginal cost of emissions reduction associated with different alternatives, which can be used to assess the level of pollution cost internalization required for enhancing the market penetration of more efficient technologies.

5. AKNOWLEDGMENTS

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