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Network synthesis for district heating with multiple heat plants

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Abstract

In this paper the first results of a new method for the configuration of district energy systems are presented. District energy systems are believed to help decreasing the CO_2-emissions due to energy services (heating, cooling, electricity and hot water), by implementing polygeneration energy conversion technologies. However, because polygeneration technologies are complex, it is meaningful to use them not just for one single building, but for several buildings connected together with a network. The configuration of the network is an important but not trivial task, mainly because the problem involves a large number integer variables and results in an MILP that needs to be optimised.

1 Symbols

Roman letters

C_{hp}: Costs for heat pump [CHF]
C_{sofc}: Costs for solid oxide fuell cell [CHF]
$C_{turbine}$: Costs for turbine [CHF]
$E_{cons}(t, k)$: Electricity consumption during period t in building k [kWh/h]
$E_{gen}(t, k)$: Electricity generated by the energy conversion device during period t in building k [kWh/h]
$E_{grid}(t, k)$: Electricity bought from the grid during period t in building k [kWh/h]
$E_{hp}(t, k)$: Electricity consumption of the heat-pump during period t in building k (if it is implemented) [kWh/h]
$E_{pump}(t, i, j)$: Electrcity consumption to pump the water in the network during period t between nodes i and j [kWh/h]
E_{sofc}: Nominal power of the solid oxide fuell cell [kW$_{el}$]
$E_{turbine}$: Nominal power of the gas turbine [kW$_{el}$]
$H_{boiler}(t, k)$: Heat generated by the boiler during period t located in building k [kWh/h]
$Dist(i, j)$: Distance between two nodes [m]
H_{boiler_max}: Maximum possible nominal power for a boiler (arbitrary high value) [kW]

$H_{cons}(t,k)$: Heat consumption during period t in building k [kWh/h]
$H_{device}(k)$: Nominal power of the device implemented in building k [kWth]
$H_{gen}(t,k)$: Heat generated by the device during period t in building k [kWh/h]
H_{hp}: Nominal power of the heat pump [kW_{th}]
$H_{net}(t,i,j)$: Energy flow during period t between nodes i and j [kWh/h]
H_{pipe}: Maximum energy that can be transported in a pipe [kW]
$H_{waste}(t,k)$: Surplus heat generated by the device located in building k during period t that is not consumed in the buildings [kWh/h]
N_{boiler}: Maximum number of boilers allowed in the network
N_{build}: Number of buildings
N_{nodes}: Number of nodes
$N_{periods}$: Number of periods
$X(k)$: Binary variable: $X(k)$=1 if a boiler is implemented in building k, $X(k)$=0 otherwise
$x(t,k)$: Binary variable: $x(t,k)$=1 if a boiler is implemented during period t in building k, $x(t,k)$=0 otherwise
$Y(i,j)$: Binary variable: $Y(i,j)$=1 if a pipe exists between heating nodes i and j, $Y(i,j)$=0 otherwise

Subscripts
i,j: Nodes at the beginning and the end of an arc (pipe)
k: Building
t : Period

2 Introduction

The reduction of CO_2-emissions is a challenge for the coming decade, especially with the implementation of the Kyoto protocol. A part from transportation, energy services (heating, cooling, electricity and hot water) are responsible for a large share of the total greenhouse gaz emissions in a country like Switzerland. Heating generates over 40% of the total emissions in Switzerland (all energy sectors considered, including transportation) [1], making it a prime candidate among energy services when considering ways to decrease the overall emissions of Switzerland. To decrease the emissions generated by the energy services, one can increase the efficiency of the different energy conversion technologies that provide these services, by combining them for instance in a polygeneration energy system. A polygeneration energy system is a system that generates more than one single energy service . An example of a such system can be a gas turbine that generates electricity and heat, or a gas turbine coupled with an absorption-chiller that produce electricity, heating and cooling. However, to ensure that polygeneration systems operate as often as possible at or near their optimal load, it is meaningful to implement systems that meet the requirements of more than just one building, in order to take advantage of the various load profiles of the buildings by compensating the fluctuations and having therefore a smoother operation. Besides, because these systems are complex and defacto difficult to operate, there are usually not justified in an individual building where no continuous professional control can be guaranteed. It is much more advantageous

to implement them in a small plant that serves several buildings, and that is managed by an energy service company. The resulting energy system with one (or more) energy plants connected to more than one building, is called district energy system. Since several buildings are connected, a district polygeneration energy system requires a distribution network, that needs to be optimally designed in terms of investment and pumping costs.
In fact, if it became obvious for people today to have a network for the distribution of the electricity from the power plants to the consumers, the picture is much different when it comes to heating. Today the majority of the buildings in western Europe are heated with individual boilers that are fed either with city gas or with oil. It is only in some cases, when the recycling of heat generated by the combustion of city waste allows it for instance, that a district heating network is implemented to use this heat. However, because of the different advantages of district heating systems, it would be beneficial to implement them not only in areas for which there is a specific opportunity like the recycling of heat released by the combustion of waste or the process of a near-by situated industry, but also in other areas. The main advantages of district heating systems are [2]:

1. Fewer sources of emission in densily populated areas.
2. Less individual boilers, thus increasing the available space in the buildings that can be used for other purposes.
3. A professional and on-going operating and maintenance of the centralised heating technology.

3 Method for the configuration of district energy systems

3.1 Description of the task

The optimization of the network synthesis for district energy systems is combinatorially complex, for several reasons. First, the number of the various combinations of different locations of energy plants is extremely high. Second, there are usually a lot of different ways to link together the buildings. Third, the diameters of the pipes are defined by a given set of possible diameters, introducing an additional discrete part into the problem. Finally the number of constraints related to a retrofit problem is usually larger than if everything could be synthesized from scratch, since it has to be considered what is already existing. For instance some pipes are already installed between given buildings, and at some places the space constraints do not allow to install pipes that are bigger than a certain diameter.
In this paper, we present the first results of a method to synthesize and optimize district energy systems. A single-period multiple-services network synthesis problem has been considered. Since the focus is on the synthesis phase, the strong assumption on the single-period demand is acceptable. Besides, in order to take advantage of polygeneration systems, heating has been considered together with electricity to start developing the method.
The proposed algorithm is used in solving district energy synthesis problems for the city of Geneva, Switzerland. However, the application of the algorithm can be easily extended to other cities since the methodology is not location dependent.

3.2 Data structuring

Figure 1 shows the method that is being developed for the configuration of the district energy system, in other words the design of the technologies together with the configuration of the network. Since this methodolgy is common to all energy services and is not specific to heating or electricity, the description of the method remains valid for all types of energy services and will not be limited to heating (unlike the results presented at the end of this paper).
At the beginning of the method, there is a structuring phase, in which all the relevant information regarding the district (in other words the buildings) for which an energy system needs to be developed, is gathered and further given as inputs to the different algorithms belonging to the method. If the types of inputs remain the same regardless of the location of the quarter analysed, the content of these three different inputs will vary greatly with the location. The three types of inputs are:

1. The list of available technologies: The technologies are organised in three subgroups: the energy conversion technologies, the storage technologies and the network technologies. To establish the list of energy conversion technologies, a comprehensive analysis of the available energy sources has to be performed. For instance, if the district is situated in the vicinity of a lake or a river, heat pumps will be part of the list of technologies. Besides, if geothermal energy is available, an organic rankine cycle can be implemented. On the other hand, considering wind mills in Geneva, to produce electricity that could be used for heat-pumps, will not lead to a feasible solution, due to the unfavorable wind conditions in Geneva
   The storage technologies can include different storage mediums and storage containers (including natural storage).
   The different network technologies are mainly characterised by the working fluid (water under pressure, CO_2).

2. Constraints: In many cases the district energy system has to fit in an existing quarter, village or small town. Therefore constraints such as the coordinates of the buildings, the layout of the roads, space constraints in existing technical galleries, constraints due to the quality of the soil... have to be taken into account in the design procedure. Besides, specific laws or regulations might exclude certain solutions if these solutions do not respect given parameters.

3. Consumption profiles: The consumption profiles for the different energy services need to be known in order to design the layout of the network, the pipes, and the pieces of equipment properly. For heating and cooling it is important not only to know the amount of energy required, but also the temperature at which this energy needs be provided and the requested power. Usually, these profiles are not only difficult to obtain, they also contain large uncertainties due to their stochastic nature. However, different methods exist nowadays that allow evaluating fairly reasonable profiles that can be used for the configuration of the network. Besides, in the configuration phase (as opposed to the operating phase), it is less important to have a very precise hourly load profile. However, typical load profiles are needed to size the energy conversion devices as well as the network.

3.3 Resolution method

The three different types of inputs are used at different stages in the resolution phase of the method. The list of **available technologies** is used as input for the genetic algorithm. The genetic algorithm solves the master problem. It is responsible for the selection of the technologies as well as for their sizes (especially for the energy conversion technologies and the storage technologies). Once the choice and size of the technologies are given, the thermodynamic models compute parameters such as the efficiencies and mass flow rates of the energy conversion technologies, as well as the capacities of the storage device(s).

The **constraints** are used in the routing algorithm to compute the maximum possible network. The maximum possible network is the one that comprises all the acceptable arcs (connections) between given nodes (buildings or plants). In practice, an arc is a pipe between a plant and a building or between two buildings. However, this pipe will not necessarily follow the shortest way between the two nodes, as this way might pass right across another building. There are therefore certain routes that have to be followed by the arcs or pipes, as shown in figure 2.

The outputs of the thermodynamic models and the routing algorithms, together with the information on **constraints** and the **load profiles**, are used as inputs to compute the configuration of the optimal network. Once the optimal network is defined, the investment as well as the operating costs can be computed, together with the overall emissions of the district energy system, and the trade-offs between these two objective can be analysed.

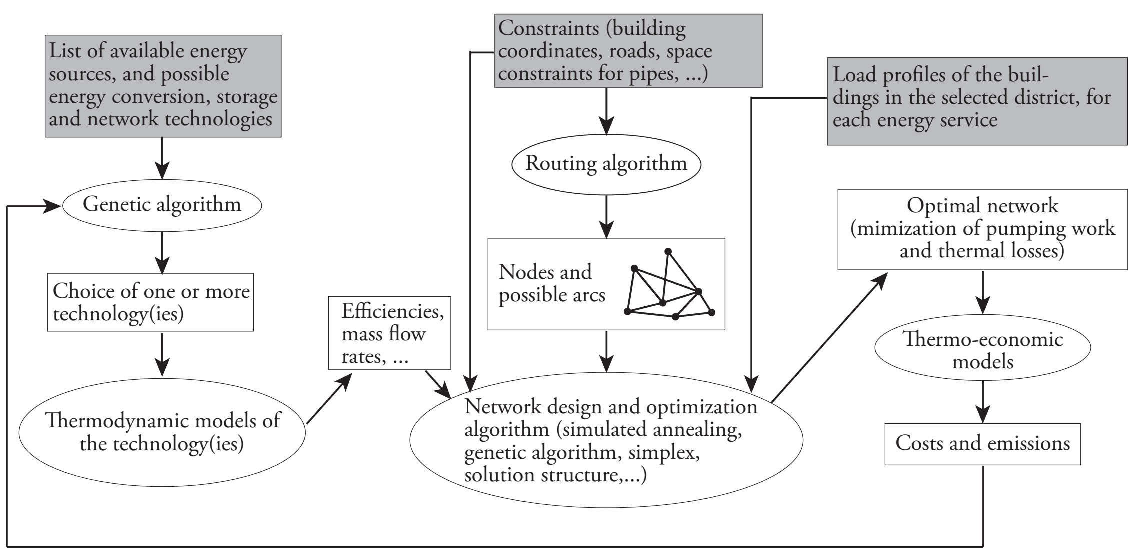

Figure 1: Resolution strategy

4 The genetic algorithm

The genetic algorithm used in this work is the Multi-Objective Optimizer MOO, developed at the Laboratory of Industrial Energy Systems of the Ecole Polytechnique Fédérale de Lausanne [3]. This optimizer uses the technique of the evolutionary algorithms to compute the trade-offs between multiple objectives. In our case, two objectives have to be minimized: the costs (including operation

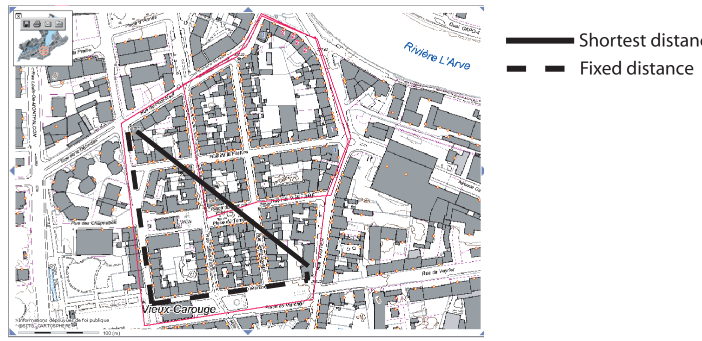

Figure 2: Difference between the fixed distance that needs be considered between two buildings, and the shortest distance geometrically

and investment) and the CO_2-emissions. In order to find the optimal configurations with the best performances in terms of CO_2-emissions and costs, the evolutionary algorithm creates a population of individuals (a set of decision variables that define a complete system configuration and the sizes of the equipment) by choosing randomly, for each individual, a set of values (genome) representing the decision variables. The "scores" or performances of each individual are then computed using the resolution strategy described previously by solving the model, i.e. using the combination of thermodynamic models, the optimal operation strategy (performance model) and the environomic model. New individuals are then selected based on the scores of the existing individuals using a set of combination operators such as mutation and crossover. After the evolution process is continued sufficiently, keeping the best individuals in the non-dominated set (according to CO_2 emissions and costs), the optimal solutions can be found. This multi-objective strategy results in an estimation of the Pareto optimal frontier (hereafter Pareto curve) that represents the set of optimal points that can be considered to be optimal in terms of one or both of the two objectives. Each point of this curve corresponds to a set of decision variables that define one configuration of the system and the optimal way of operating it on a yearly basis.
This paper presents the method for designing the network. The MOO algorithm selects the size and type of device that will be implemented in each building. Note that the MOO algorithm can of course choose to put no energy conversion device in one building (size = 0). There are therefore 2 decision variables for each building. Unlike the usual case, the size of the devices is expressed in kWth, even for the solid oxide fuel cell and the gas turbine. The electrical output of these devices is computed from the thermal output as explained in section 6. The devices can be chosen among the three following energy conversion technologies: heat-pump, solid oxide fuel cell or gas turbine. If the total size of the energy conversion technologies chosen by the MOO algorithm is too small to meet all the heating and electricity requirements, additional boilers can be used in the buildings for heating purposes, and electricity can be taken from the grid.

5 The network design and optimization algorithm

The network design and optimization algorithm is a mixed integer linear programming model implementing the AMPL programming language [4], combined with the Cplex solver [5]. The network is designed by solving the following problem:

$$\min \sum_{i,j=1}^{N} (Y(i,j) \cdot Distance(i,j)) \tag{1}$$

Under the constraints:

$$H_{cons}(t,k) + H_{waste}(t,k) = H_{gen}(t,k) + H_{boiler}(t,k) + \sum_{j=1}^{N_{nodes}} H_{net}(t,j,k) - \sum_{j=1}^{N_{nodes}} H_{net}(t,k,j) \tag{2}$$
$$\forall t = 1..N_{periods} \quad \forall k = 1..N_{build}$$

$$E_{cons}(t,k) + \sum_{i,j=1}^{Nbuild} E_{pump}(t,i,j) + E_{hp}(t,k) = E_{gen}(t,k) + E_{grid}(t,k) \tag{3}$$
$$\forall t = 1..N_{periods} \quad \forall k = 1..N_{build}$$

$$H_{gen}(t,k) \leq H_{device}(k) \quad \forall t = 1..N_{periods} \quad \forall k = 1..N_{build} \tag{4}$$

$$\sum_{k=1}^{N_{build}} X(k) = N_{boiler} \quad \forall k = 1..N_{build} \tag{5}$$

$$H_{boiler}(t,k) \leq x(t,k) \cdot H_{boiler\_max} \quad \forall t = 1..N_{periods} \quad \forall k = 1..N_{build} \tag{6}$$

$$\sum_{k=1}^{N_{build}} H_{boiler}(t,k) = \begin{cases} 0 \ if \ \sum_{k=1}^{N_{build}} H_{device}(k) \geq \sum_{k=1}^{N_{build}} H_{cons}(t,k) \\ \sum_{k=1}^{N_{build}} H_{cons}(t,k) - \sum_{k=1}^{N_{build}} H_{device}(k) \ else \end{cases} \tag{7}$$

$$H_{net}(t,i,j) \leq Y(i,j) \cdot H_{pipe} \quad \forall t = 1..N_{periods} \quad \forall i,j = 1..N_{nodes} \tag{8}$$

The objective function, equation 1, expresses the goal of having a network as small as possible in order to avoid too large pumping costs. Equations 2 and 3 are the heat and electricity balances. In equation 2 $H_{net}(t,j,k)$ represents the heat provided to building k by the network, and $H_{net}(t,k,j)$ the heat provided by building k to the network, to be used by other buildings. $H_{waste}(t,k)$ is the surplus of heat generated by the devices (see assumption 2). In equation 4, $E_{pump}(t,i,j)$ are the pumping costs of the working fluid in the network, from building i to building j. In equation 5 the variable N_{boiler} has been set to 1, thus allowing only one boiler to be implemented in the energy system. Besides, the size of the boiler, which is given as a result of the optimisation, may only be greater than 0 if the total size of all the heating devices is smaller than the heating requirements (equation **??**). Finally equation 8 guarantees that the configuration of the network doesn't change but remains the same from one period to the other. Besides H_{pipe} corresponds to the maximum power that can be transported in standard pipes that can be found on the market for district networks.

Following assumptions have been made:

1. No storage is considered in this work.
2. The devices are not allowed to operate at a part load smaller than 30% of their design load. If the MOO algorithm chooses to implement devices for a total size that is bigger than the total heat consumption, waste heat is being generated.
3. The efficiencies of the devices (thermal and electrical) remain the same at part load than at design load.
4. Only one boiler is allowed to be implemented in the whole network.
5. The solid oxide fuel cell(s), the gas turbine(s) and the boiler are operated with natural gas.
6. The working fluid of the network is supposed to be hot water.
7. In order to keep the linearity of the model, the pumping power has been estimated simply by assuming straight pipes, an average velocity in the pipes of 4 m/s, an average diameter of the pipes of 150 mm and a friction-factor of 0.02.
8. The heat generation level of the devices is governed by the heating requirements. Since electricity will be generated by the energy system if solid oxide fuel cells or gas turbines are chosen, this electricity will not match exactly with the requirements of the building. If too much electricity is generated, it can be released to the grid. However, no financial benefits are accounted for.

6 Modeling of the energy conversion technologies

The energy conversion technologies have been modeled by simple relations. For the heat-pump, a coefficient of performance of 3 has been chosen. For the solid oxide fuel cell, both the electrical and thermal efficiencies have been set to 45%. For the gas turbine, the electrical efficiency for different sizes of turbines has been computed by making a curve fitting of data found in the literature [6]. Assuming a total efficiency (electrical plus thermal) of 80%, the thermal efficiency of the gas turbine could be calculated.
Although it would be very easy to add thermodynamic models to the proposed method, like explained in section 3, it hasn't been done in this work in order to avoid slowing down the whole computation when the focus is set on the configuration of the network and not on the optimisation of the devices.

7 CO_2-emissions and costs

For the CO_2-emissions, only the emissions resulting from the operation of the devices have been accounted for, as it has been shown in a previous work [8] that for such type of energy systems the emissions related to the manufacturing of the devices are negligible compared with the operation emissions. Since all the devices are assumed to be operated with natural gas, the emissions have been computed by assuming a value of 0.225 kg-CO_2/kWh (0.197 kg-CO_2/kWh for the combustion of the gas [10] and 0.028 kg-CO_2/kWh for the preparation and transportation [9]). For the grid, a value of 1.19e-18 kg-CO_2/kWh, corresponding to the swiss mix [9], has been admitted. Like for the modeling of the energy conversion technologies, the costs are computed with simple relations found in the literature:

1. Heat-pump [9]:
   If the heat pump is smaller than 350 kW_{th} (condenser output), following relation is used:
   $$C_{hp} = 14901 \cdot \left(\frac{H_{hp} \cdot 10^3}{95000} \right)^{0.6} \tag{9}$$
   If the heat-pump is bigger than 350 kW_{th} (condenser output), following relation is used:
   $$C_{hp} = 8.747 \cdot 10^6 \cdot \left(\frac{H_{hp} \cdot 10^3}{25 \cdot 10^6} \right)^{0.9} \tag{10}$$
   For both relations the size of the heat-pump is in [kW_{th}] and the costs in [CHF].
2. Solid Oxide Fuel Cell [10]:
   $$C_{sofc} = 1500 \cdot E_{sofc} \cdot 10^3 \tag{11}$$
   The size is given in [kW_{el}] and the costs in [CHF].
3. Gas turbine [10]:
   $$C_{turbine} = 2350 \cdot (E_{turbine} \cdot 10^3)^{0.8503} \tag{12}$$
   The size is given in [kW_{el}] and the costs in [CHF].

8 Results

The method developed was first tested on a small invented network comprising 8 buildings and 9 arcs (see figure 3), before being further applied onto an existing quarter in Geneva. The selected quarter comprises 44 buildings and 272 arcs. The large number of arcs is partially due to the fact that in the georeferenced data base of the Canton of Geneva, if a long road makes several curves, the road will be characterised in the data base by more than one arc, since an arc is always a straight line.

In the case of the selected existing quarter, the routing algorithm proved to be efficient to process the data from the data base of the Canton of Geneva so it could be used in the network synthesis algorithm. However, the resolution time for the network synthesis algorithm to compute a network

Cluster	HP	SOFC	GT	Boiler
1	2-3	0	0	0
2	1-2	0	1	0
3	0	0	1	0
4	0	1	0	0
5	0-2	0	2	0
6	0	0	2	0
7	0	0	2	0
8	1	0	2	0

Table 1: Devices used in each cluster

configuration lasted from one minute, up to over an hour, depending on the number and size of devices selected by the MOO algorithm. This computation time is due to the large number of integer variables. Knowing that it takes far over 10000 calculations for MOO to converge, the method shows to be unrealistic if no acceleration steps are introduced. For instance following accelerations can be introduced:

1. Reduce the number of integer variables. For instance one could impose the building in which certain devices like the boiler can be implemented, instead of leaving the choice to the network configuration algorithm: this simplification reduces the number of integer variables without reducing the pertinence of the method, since a boiler for a district energy system usually cannot be implemented just in any building.

2. Implement algorithms such as the accelerated branch-and-bound algorithm that aims at reducing the computing time by more efficiently searching the solution space (see for instance [11]).

In this section the results for the small test network are presented. The network configuration of the selected quarter downtown Geneva is left over for future work, after the acceleration steps will be introduced in the method.
Figure 4 shows the results for the test-network on a Pareto curve. On this curve, each point represents a configuration with given devices and a network. On this curve, the CO_2-emissions are particularly low, especially for cluster 1, in which only heat-pumps are implemented. These extremely low values are a consequence of the fact that for these calculations the CO_2-emissions of the swiss grid have been chosen as reference. Since Switzerland produces electricity mainly with hydraulic and nuclear power plants, there are almost no emissions. However, since Switzerland imports about as much electricity as it exports, new optimisations have to be run, considering the CO_2-emissions value of the european grid.
8 clusters can be identified (the numbers of the clusters are given next to each cluster, on the figure). The devices implemented in each cluster are given in table 8.

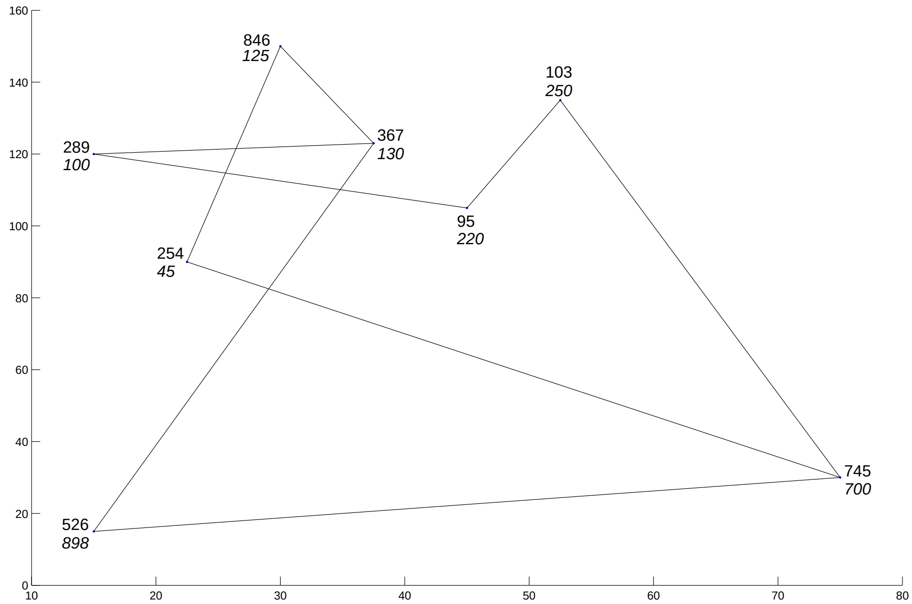

Figure 3: Test network: the figures represent the heat consumptions (regular font) and the electricity consumptions (italic font) in kWh/h

The main difference between the most costly and the less costly solutions in clusters 2 and 5 is the share of each type of devices in the total heat generation. In cluster 2 for instance the size of the gas turbine increases from 100 to 3250 kW (the total heating requirement is 3225 kWh/h), resulting in a decrease of the heat-pump(s) from 3235 kW to 105 kW. In cluster 5 the size of the gas turbine increases from 2140 to 5500 kW.
Figures 5 and 6 show the network for two different configurations (solutions 1 and 2 on figure 4). The thin lines represent the possible connections, and the thick lines the computed network. Besides the squares represent heat-pumps and the triangles represent gas turbines. The size of the devices are also indicated on the figure.

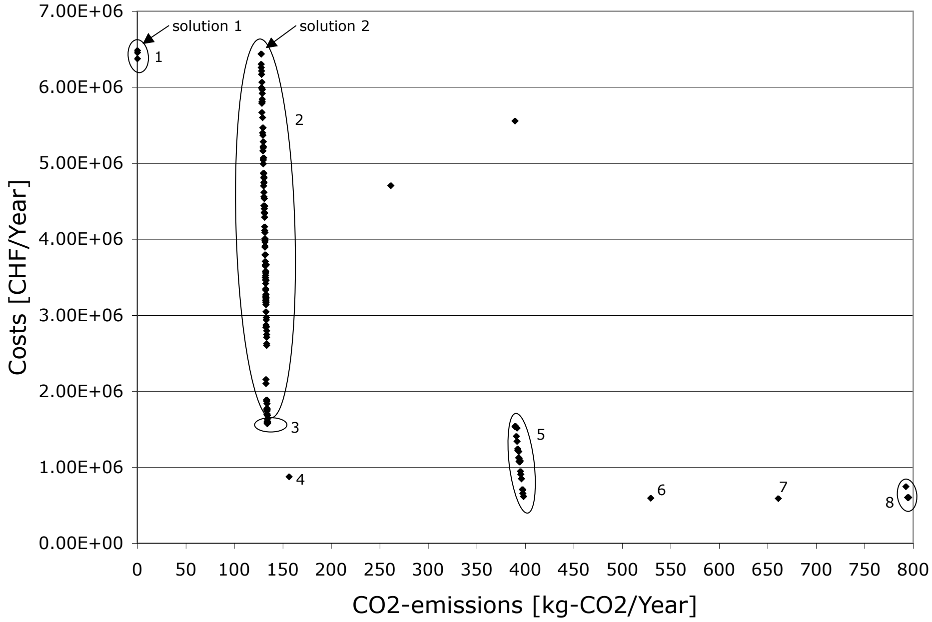

Figure 4: Pareto curves of the results

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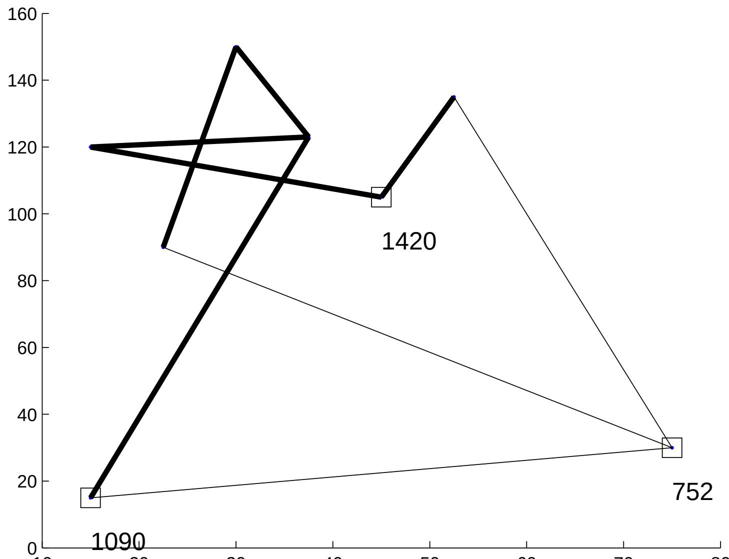

Figure 5: Network configuration of solution 1

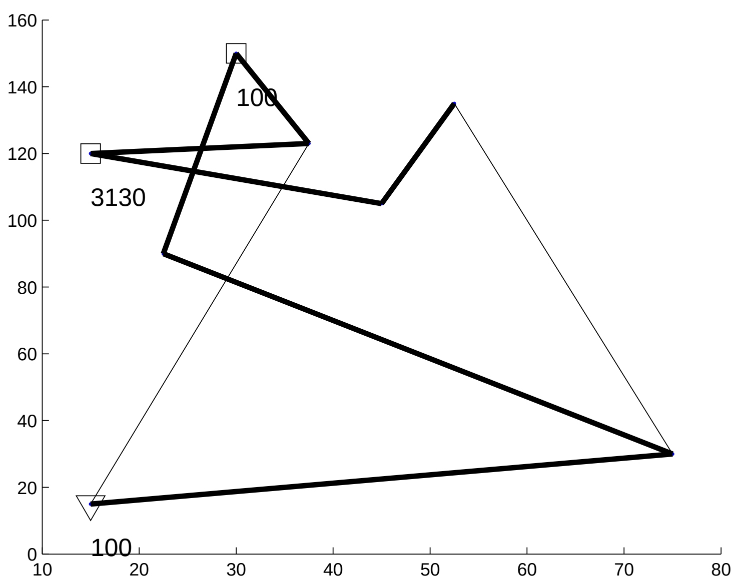

Figure 6: Network configuration of solution 2

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