Network synthesis for a district energy system: a step towards sustainability

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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, connected to a group of buildings over a network. The synthesis of the network is an important but not trivial task, mainly because the problem involves a large number of integer variables and results in an mixed integer linear programming problem (MILP) that needs to be optimised.

Keywords: District heating, Network synthesis, MILP, CO2-emissions.

1. Symbols

Roman letters

A: Set of arcs in the maximal structure
A_o: Fixed investment cost of operating unit o [CHF]
B_o: Proportional investment cost of operating unit o [CHF]
C_b: Investment costs of the boiler [CHF]
C_{hp}: Investment costs of the heat pump [CHF]
C_m: Price of raw material m [CHF]
H_b: Nominal power of the boiler [kW$_{th}$]
H_{hp}: Nominal power of the heat pump [kW$_{th}$]
M: Set of materials
M: Arbitrary large number
O: Set of operating units
P: Set of products
P_m: Minimum amount of required product m [kg]
R: Set of raw materials
$R_{o,m}$: Amount of material m produced or required by operating unit o if x_o=1
S_m: Maximum amount of available raw material m [kg]
x_o: Size of operating unit o

y_o: Binary variable: 1 if unit o is present, 0 otherwise

2. Introduction

The reduction of CO_2-emissions is a challenge for the coming decade, especially with the implementation of the Kyoto protocol. Besides transportation, energy services (heating, cooling, electricity and hot water) are responsible for a large share of the total greenhouse gaz emissions. For example in Switzerland, heating generates over 40% of the total emissions (all energy sectors considered, including transportation) [1]-[2], making it a priority candidate among energy services when considering ways to decrease the overall emissions of Switzerland. To decrease the emissions generated by the energy services, one way is to increase the efficiency of the different energy conversion technologies that provide these services, by combining them in a polygeneration energy system. A polygeneration energy system is a system that generates more than one single energy service. Advanced systems allow to save over 60% of the energy resources and emissions compared to conventional solutions [2]. However, to ensure that polygeneration systems operate as often as possible at or near their optimal load, they should be implemented so as to meet the requirements of more than just one building. By doing so, one can 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) polygeneration energy conversion technologies, together with the network connecting the technologies and the different buildings, is called district energy system.

3. Method for the configuration of district energy systems

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 and sizes of energy plants is extremely high. Second, there are usually a lot of different ways to link the buildings together. Third, the diameters of the pipes are usually defined by a given, non continuous set of possible diameters. Finally, the number of constraints related to a retrofit problem is usually larger than for a blank-sheet design. In this paper, we present the first results of an algorithm based on the graph theory approach, to synthesize and optimize networks for district energy systems. A single-period, single-service, multiple-ressources network synthesis problem has been considered. Since the focus is on the synthesis phase, considering single period instead of multiple period is acceptable. Besides, although the aim is to synthesize networks with polygeneration energy conversion technologies, the focus has been set on heating only (single-service), in this first step. Finally the network synthesis algorithm has the choice to implement a single or multiples ressource(s) (energy conversion technologies) in the network.

4. Graph theory approach

The proposed algorithm is based on the graph theory approach developed by Friedler et al. [3]. The graph theory approach allows to generate a mathematical representation of a superstructure, a superstructure being the unity of all production units and materials (raw materials, intermediates and final products) involved in the production of the required output. In the case analysed here, the raw materials are the inputs of the energy conversion technologies (for instance natural gas in the case of boilers and electricity in the case of heat-pumps), the final product is the heat delivered to each building, and the operating units are the energy converison technologies (heat-pumps and boilers) as well as the pipes transfering the water from the energy conversion technologies to the consumers and back. The mathematical representation enables the development of efficient algorithms for the synthesis and optimization of an optimal solution structure. The optimal solution structure is the network, among all the possible networks, that minimizes for instance the costs or the CO2-emissions.
To compute the optimal solution structure, the graph theory approach is combined with the accelerated branch-and-bound algorithm (ABB) [4]. The main equations of the ABB algorithm are given in fig.1. The first term of the objective function corresponds to the costs of the operating units, the second to the cost of the raw materials. The first constraint states that the leaving material m (on arcs or as product) is less or equal to the material entering the node (on arcs or as raw material). The second constraint ensures that the size of an operating unit is 0 if it is not present in a solution structure.
Fig.2 shows a very simple example network including one heating plant (1), several possible connections (2-15), and the buildings to be heated, as well as the corresponding superstructure in the so-called process graph (P-graph).

$$\min \sum_{o\in \mathrm{O}} \left(A_o \cdot y_o + B_o \cdot x_o\right) + \sum_{m\in \mathrm{R}} \left(C_m \cdot \sum_{\{o\in \mathrm{O}:(m,o)\in \mathrm{A}\}} \left(R_{o,m} \cdot x_o\right) \right)$$

$$s.t.$$

$$\sum_{\{o\in \mathrm{O}:(m,o)\in \mathrm{A}\}} \left(R_{o,m} \cdot x_o\right) + P_m \le \sum_{\{o\in \mathrm{O}:(o,m)\in \mathrm{A}\}} \left(R_{o,m} \cdot x_o\right) + S_m \qquad \forall m \in \mathrm{M}$$

$$x_o \le y_o \cdot M \qquad \forall o \in \mathrm{O}$$

Figure 1. Main equations of the ABB algorithm

5. Mathematical model for the single-period, single-service and multiple-resources network

Following characteristics have been considered to build the superstructure:

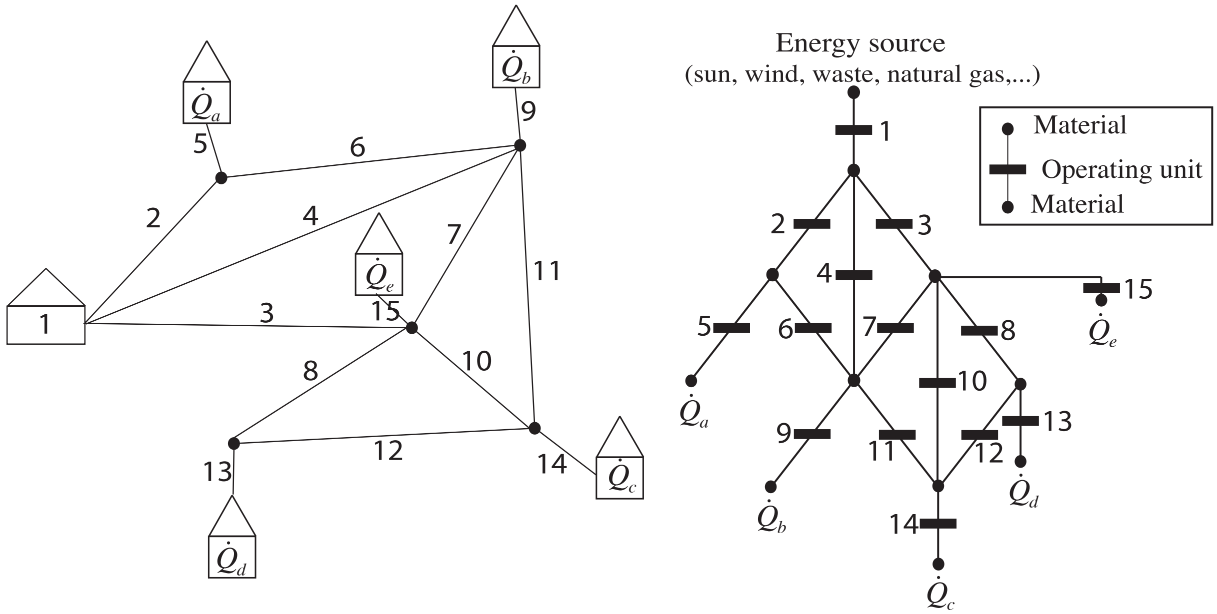

Figure 2. Left: District with several possible connections; Right: Resulting P-graph of the superstructure (Q_i: power delivered to building i): Operating unit 1 is a plant, and the others are pipes.

1. The energy conversion technologies for heating are boilers and heat-pumps. They can be located in one or more building(s) belonging to the district.

2. The geographical distance between two points is fixed. This distance is computed using GIS (Geographical Information System). It does not necessarily correspond to the shortest geometrical distance between the two points (Fig. 5).

3. The return pipes are parallel to the ongoing pipes to the buildings, and have the same diameters. The ongoing and return pipes are represented by a single operating unit on the P-graph. (Ongoing pipe: pipe carrying the hot water from the heating plant to the buildings; return pipe: pipe carrying the cold water back from the buildings to the heating plant.)

4. Different constraints, e.g. spatial constraints in a technical gallery/rack, constraints on the size of pipes (availability on the market), can be easily implemented.

5. In the resulting optimal solution sturcture there can be splitting, but no mixing, between the pipes going to the buildings, **except if one of the two pipes comes from a plant**.

6. The temperature level at which the heat needs be delivered and the heat losses have not yet been taken into account in the optimization.

Table 1
Heat requirement in each building

Building	Consumption [kW]
1	526
2	745
3	254
4	95
5	367
6	289
7	846
8	103

Table 2
Selected connections: diameters of the pipes and power transfered

	Diameter [mm]	Power transfered [kW]
P1_2	150	745
P3_1	150	1271
P5_4	50	195
P5_7	150	949
P6_3	150	1525
P6_5	150	1411
P7_8	50	1103

6. Results

The optimization has been done to minimize the total annual costs (investment and operation). The model (102 continuous and 102 integer variables) was written so that the algorithm had the choice to implement or not a boiler and/or a heat-pump in each building. The choice of the size and number of technologies was left over to the algorithm. Following costs were applied, based on [5] and [6] :

Energy conversion technologies:
Costs for the boiler: $C_b = 27H_{hp} + 10000$ CHF
Costs for the heat-pump: $C_{hp} = 405H_{hp} + 340000$ CHF
Costs for the pipes as a function of the diameter in mm:
50 mm: 1200 CHF/m; 80 mm: 1350 CHF/m; 150 mm: 1750 CHF/m
Costs for the utilities (raw materials):
Electricity: 0.13 CHF/kWh
Natural gas: 0.05 CHF/kWh

For the boiler(s) an efficiency of 90% was chosen and for the heat-pump(s) a coefficient of performance of 4 is selected, assuming that a low temperature heating system is available in the building. Fig. 3 and table 2 show the optimal solution structure for a test network. On this figure, the broken lines represent the possible connections between the buildings, the thick and thin continuous lines show the connections that have been selected by the algorithm and that are part of the optimal solution structure, as a function of the diameter of the pipe. One can see that the optimal solution comprises one heat-pump but no boilers, although boilers have lower investment costs. This is due to the higher efficiency of the heat-pump when compared with a boiler. The total annual costs for the optimal network is 868'000 CHF (313 days, 24 hours per day). (On the figure **HP** means heat-pump, **PX_Y** is a pipe from building X to building Y).
Fig. 4 shows the optimal solution structure assuming that between buildings 1 and 3 one cannot implement pipes with a diameter larger than 50 mm (costs: 868'000 CHF/year).

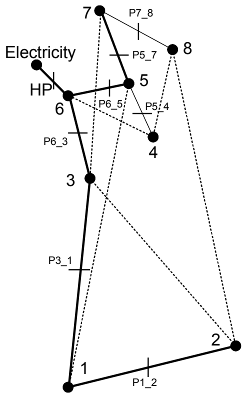

Figure 3. Optimal network (no constraint)

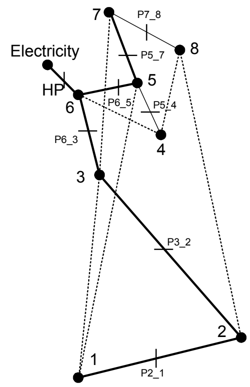

Figure 4. Optimal network with constraints

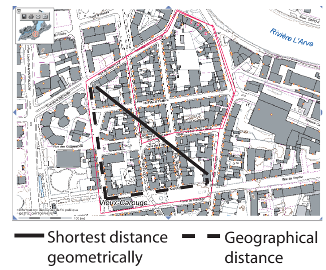

Figure 5. Difference between the fixed distance and the shortest distance geometrically

7. Conclusion

A method that applies the P-graph approach has been developed to synthesize district energy systems. The method developed allows to consider constraints like diameters, restricted paths and the possibility of decentralised production of heat with multiple units. The system developed is integrated with a GIS system and technology data base systems. The network synthesis method will be further developed to be integrated in a method that will consider the optimal management issues multi-period problems.

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