17th European Symposium on Computer Aided Process Engineering – ESCAPE17
V. Plesu and P.S. Agachi (Editors)

Design and optimization of district energy systems

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Abstract

District energy systems have the potential to decrease the CO_2 emissions linked to energy services (heating, hot water, cooling and electricity), thanks to the implementation of large polygeneration energy conversion technologies, connected to a group of buildings over a network. The synthesis of district energy systems requires a large number of integer and continuous variables involved in non linear models, resulting in a mixed integer non linear programming problem (MINLP). A new method is being developed to design district energy systems, by decomposing the multi-objective optimization problem into two sub-problems: a master optimization problem and a slave optimization problem. In this paper, the method developed as well as the first results of the complete resolution procedure are presented.

Keywords

District energy system, Network synthesis, MINLP, Costs, CO_2 emissions

1. Introduction

The reduction of CO_2 emissions is a challenge for the coming decade, especially with the implementation of the Kyoto protocol. Beside transportation, heating is responsible for a large share of the total greenhouse gas emissions. For example in Switzerland, heating alone generates over 40% of the total emissions (all energy sectors considered, including transportation) [1]-[3], making it a priority candidate among energy services when considering ways to decrease the overall emissions of Switzerland. Besides, the demands for cooling keep increasing. To decrease the emissions generated by energy services (heating, hot water, cooling or electricity), one way is to consider energy conversion technologies that simultaneously provide multiple services (polygeneration). In the case of heating for instance, large polygeneration systems allow to save over 60% of the energy resources and emissions compared to conventional solutions [3], not least because of the possibility to use resources such as the cold water of a lake for instance. The integration of large efficient energy conversion technologies with district heating/cooling networks is therefore a possible solution to reduce the emissions. The resulting 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*.

2. Method for the design and optimization of district energy systems

The design of a district energy system that minimizes CO_2 emissions and costs requires the development of a new appropriate method. The method developed and shown in this paper (figure 1) comprises a structuring phase in which all the relevant data regarding the district considered are gathered (consumption profiles for the different energy services, location of the buildings, allowed connections between the buildings,…), followed by an optimization phase in which the optimal district energy system is designed, and finally a post-processing phase in which the system performance, namely the total CO_2 emissions and costs, are computed. Due to the complexity of the analyzed problem, the optimization phase is decomposed in a master optimization problem and a slave optimization problem. This decomposition strategy has already been successfully implemented in a previous study on the optimal operation management of an SOFC-based energy system for a building downtown Tokyo [5]. The principles of the method have been explained in details elsewhere [6], so that only the important features of the optimization phase will be explained hereunder.

3. Optimization phase

The optimization phase is decomposed into two parts, the non linear part is solved by a *multi-objective* master optimization problem using an evolutionary algorithm [2], together with the thermodynamic models of the energy conversion technologies. The mixed integer linear part (MILP) is solved by a *mono-objective* slave optimization problem connected to the master optimization problem, and which uses the branch-and-bound algorithm combined with the simplex method. The set of decision variables linked to the master optimization is called the *master set* of decision variables, and the set of decision variables linked to the slave optimization the *slave set* of decision variables. The combination of both sets of decision variables is the *extended set*.

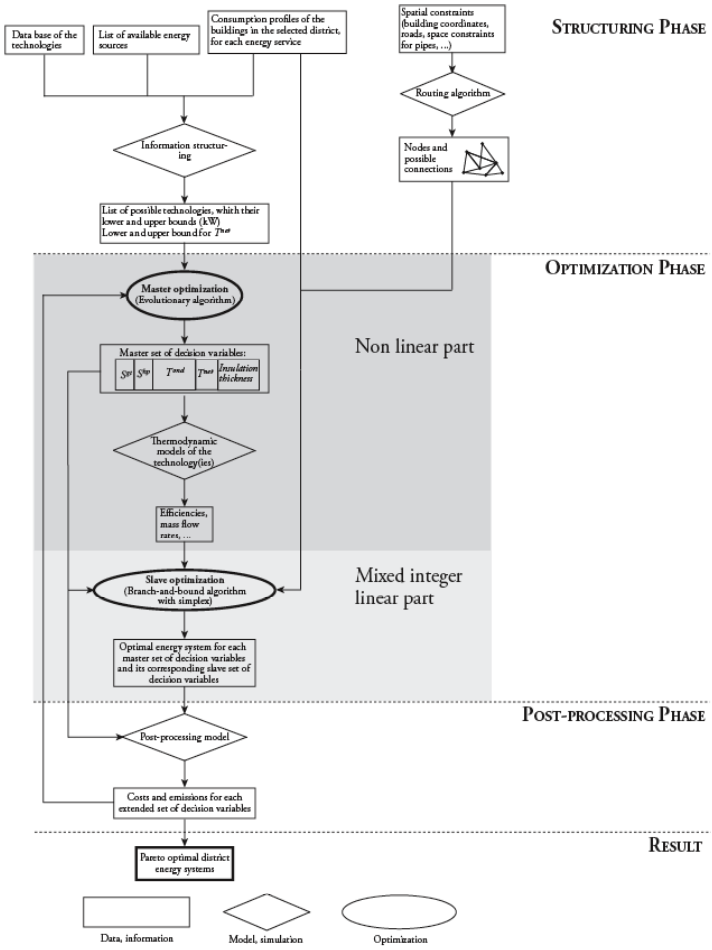

Figure 1: Resolution strategy

3.1. Multi-objective master optimization problem

The two objectives of the master optimization problem are the minimization of CO_2 emissions (resulting from to the operation of the network energy system) and the total costs (including both the operation and investment of the network energy system). The master optimization takes care of following variables: the design size and characteristics of the network heating technologies (for the example shown here: the choice is given between a gas turbine, a gas engine and/or a heat-pump), the design size of the network cooling technologies, the network supply temperatures for heating and cooling (in this case a choice of maximum two compression chillers), the insulation thickness of the pipes, and the value of the CO_2 tax. (Note that the *network* technologies which are optimized in the master optimization are technologies that are connected to the network and that meet the requirements of more than one building, whereas the *local* technologies, optimized in the slave optimization, only meet the requirements of the building in which they are implemented.)

3.2. Single-objective slave optimization problem

The slave optimization problem defines the optimal network design and operation, given the master set of decision variables (and the resulting outputs from the thermodynamic models), the consumption profiles and the outputs from the routing algorithm (see figure 1). The slave optimization problem is a mono-objective optimization problem, having the minimization of the costs as objective. The optimal network design and operation model includes the optimal design of the network, and the optimal operation strategy. Since both heating (including hot water) and cooling are considered, the slave optimization takes care simultaneously of two networks (the heating and the cooling network). The slave optimization takes care of design variables such as node selections for the location of the network technologies (integer variable), connections between the nodes (integer variable), diameters of the pipes connecting nodes, design size of the local technologies, as well as operational variables such as the hourly electricity consumptions to pump the water in the pipes, heat distribution to the buildings, cooling distribution to the buildings, electricity distribution to the buildings, mass flow rate of water through the pipes in the heating or cooling network, operation of the network and local technologies, and consumptions (natural gas, oil and electricity purchased from the grid). In order to prevent infeasible problems, the slave optimization allows the integration of local technologies in case the capacity of the network energy technologies isn't sufficient to meet the requirements of all the consumers or if the laying out of a pipe to a remote building or a building with small consumptions is more expensive than the implementation of a local technology. The network design and optimization model has the choice of following types of technologies: boilers, air/water heat pumps and water/water heat pumps.

4. Assumptions

The following assumptions and simplifications have been made: the district considered comprises 12 nodes (among which 8 nodes represent buildings), with a maximum total heating load (including space heating and hot water) of 4930 kW and a maximum total cooling load of 645 kW, the strategy adopted in the slave optimization problem is a heat load following strategy, the network-fluid is water, the pressure losses amount 300 Pa/m with a velocity of the water in the piping of 3 m/s, the heat loss coefficient for the conduction through the pipes amounts to 0.04 [W/mK] and for convection outside the pipe to 8

[W/mK], the convection inside the pipes has been neglected in the calculation of the overall heat transfer coefficient [4], the atmospheric temperature has been set to 10°C and the temperature of the lake to 5°C, minimum part loads are set for each network technology and the network technologies producing electricity are connected to the buildings of the district over the grid. Finally, a two-period profile has been used to develop the method, which means that two periods are used to describe the consumptions for the different energy services throughout the day. The two periods have been assumed to last 12 hours/day each for 313 days per year. With this definition, the master optimization takes care of 13 variables and the slave optimization of 384 binary variables and 3431 linear variables for each evaluation.

5. Results

The Pareto curve obtained after 500 evaluations of the master optimization are shown in figure 2. The resolution time amounted to 8 hours of CPU time on an Intel Pentium4 2'800 Mhz [7]. Each point on this figure represents a configuration of a given district energy system, with its associated yearly CO_2 emissions [kg-CO_2/year] and costs [CHF/year]. A configuration is characterized by the types and sizes of the network and/or local technologies, the layout of the pipes, the supply temperatures and the CO_2 tax among the most important features. Cluster 1 is basically characterized by large network technologies for heating and cooling and high network supply temperatures. Large network technologies means that the majority, or all the requirements in the district, can be met by the network technologies and that the supply temperatures are above the highest required temperature level for heating and below the lowest temperature for cooling. Cluster 2 has basically the same characteristics as cluster 1, except that the network technologies for heating can meet only about half of the total heating and hot water requirements. The configuration of cluster 3 has a supply temperature for heating in the same range than in clusters 1 and 2, but a total size for the network heating technologies in the range of cluster 4. In cluster 4, the network supply temperatures, especially for heating, are low and allow to meet the requirements of just 2-3 buildings in the network. Consequently, the size of the network technologies for heating are smaller than for the other clusters.

6. Conclusions and future work

The decomposition method combining an multi-objective optimization using an evolutionary algorithm with a MILP optimization has been developed for the design and optimization of large scale district energy systems. The method proves to be able to solve the problems, however with a long resolution time. Future work includes above all a reduction of this total resolution time and the application of the method on real districts (this is being currently performed on some test districts).

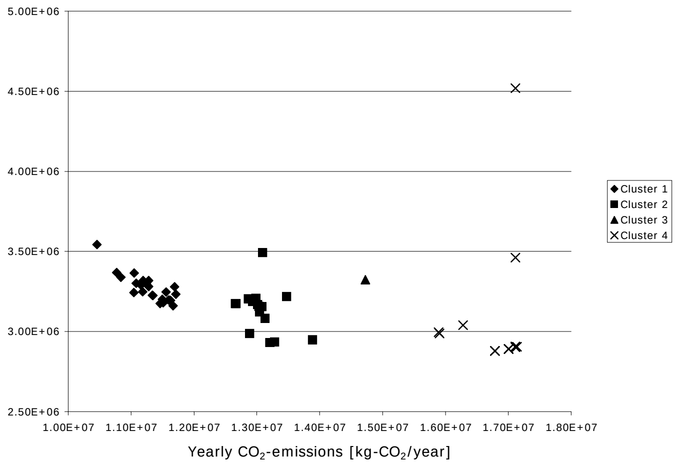

Figure 2: Pareto curve of the results

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