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Multicriteria optimization of a distributed energy supply system for an industrial area

D. Buoro [a], M. Casisi [a], A. De Nardi [b], P. Pinamonti [a], M. Reini [b,*]

[a] Dept. of Electrical, Management and Mechanical Engineering, University of Udine, Italy
[b] Dept. of Engineering and Architecture, University of Trieste, Italy

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ABSTRACT

In the paper a multi-objective optimization model for distributed energy supply systems optimization is presented. The superstructure of the system comprehends a district heating network that connects the users to each other, small-scale CHP systems, large centralized solar plant and a thermal storage. The optimization has to determine the optimal structure of the system, the size of each component inside the optimal solution and the optimal operation strategy. The multi-objective optimization is based on a MILP (Mixed Integer Linear Programming) model and takes into account as objective function a linear combination of the annual cost for owning, maintaining and operating the whole system and the CO_2 emissions associated to the system operation. The model allows to obtain different optimal solutions by varying the relative weight of the economic and the environmental objectives. In this way the Pareto Front is identified and the possible improvements in both economic and environmental terms can be highlighted. The model has been applied to a specific case study and it has been optimized for different superstructure configurations and for two different values of the electricity carbon intensity. The obtained results show that the solar plant, coupled with the optimal thermal storage, allows reaching both environmental and economic goals.

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1. Introduction

Distributed energy systems have already been recognized as an efficient and reliable alternative to the traditional energy supply [1]. It must be said also that nowadays a purely economic analysis is not anymore sufficient due to growing environmental concerns like global warming and depletion of fossil fuel reserves. Therefore, the operation problems become more challenging when the environmental burdens should be minimized at the same time when costs have to be minimized too [2]. The reason is that the minimization of costs and pollutant emissions are normally contradictory objectives, as it is often expensive to utilize environmentally friendly technologies.

The multi-objective optimization can help to solve this problem combining the supply energy cost together with the environmental impact. These goals have to be both minimized. Multi-objective optimization tackles the issue of conflicting objective functions, finding a set of solutions by varying the impact of each objective function in the global optimum. For such solutions, called Pareto optimal solutions or non-dominated solutions, no improvement is possible without sacrificing the other objective functions [3]. Reviews on multicriteria analysis and examples of multi-objective optimizations of distributed energy supply systems can be found in [4–9].

The paper illustrates an optimization model that helps to determine the optimal configuration and operation of a distributed energy supply system and its applications to the energy supply system serving nine industrial facilities, closely located in the same industrial area. The nine users may be connected to each other through a district heating network (DHN) of fixed size and layout. Heating and electric demands are known in advance and they can be satisfied by small-scale CHP systems (ICE or μTG), properly located at or near the end-users. Conventional integration boilers can also be installed inside the factories or in a centralized plant and each user is free to purchase and sell electricity from/to the national grid.

The paper also introduces the integration between conventional power sources and renewable energies, designing a solar district heating plant coupled with a long term thermal energy storage. This alternative is increasing in importance, as it is a valid solution

* Corresponding author.
E-mail addresses: dario.buoro@uniud.it (D. Buoro), melchiorre.casisi@uniud.it (M. Casisi), ing.alberto.denardi@gmail.com (A. De Nardi), piero.pinamonti@uniud.it (P. Pinamonti), reini@units.it (M. Reini).

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to overcome the mismatch problem between the availability of the solar source and the energy user demands, especially for domestic applications. Examples of this kind of integrated systems are described in [10–12], without performing an explicit optimization. As all users can be connected together through the DHN, the heat produced by the solar thermal plant and by the production units may be exchanged to one another or sent to the thermal storage. In this way each single distributed user cannot be optimized separately, because the energy flows exchanged with the DHN and the thermal storage are not known in advance. This is the reason why the model presented in the paper faces the optimization of the whole distributed generation system all at once, differently from examples which can be easily found in literature where the optimization of cogeneration systems of different complexity is performed with reference to a single user.

The model used to solve the optimization problem is based on a Mixed Integer Linear Programming (MILP). In previous works of the authors, MILP models were developed to optimize the design and operation of distributed CHP systems in a tertiary sector scenario, considering different technologies and the effects of various economic support policies [13–16]. A similar model was applied to an industrial area considering also the thermal inertia of the network in [17].

In this paper, the two objective functions of the model to be minimized are the total CO_2 emissions during operations and the total annual cost for owning, maintaining and operating the whole distributed system. The optimization is subject to the constraints that express component operation characteristics, energy balances of nodes and district heating network behavior. The optimization specifies the size, the kind and the location of cogeneration equipment and integration boilers, the size of the solar thermal plant and of the heat storage, as well as the optimal operation of each component included in the optimal solution.

In the case study the multi-objective optimization model is applied to nine factories, located in the same industrial area, and the Pareto frontiers associated to four different energy supply system configurations and to two different values of the electricity carbon intensity are evaluated. The results of the optimizations can be used to identify the best trade-off solutions.

The aim of the paper is to evaluate the economic and environmental benefits of the integration between cogeneration units, solar thermal field and thermal energy storage when the optimal synthesis and operation of the whole energy supply system are adopted.

2. Optimization model

The proposed model aims at providing decision support to planners for selecting the configuration system and the operating levels of various generation units throughout the planning period.

A lot of research has been carried out recently to optimize the design and operation of distributed energy supply systems [3,18–20] integrated also with the district heating network [21–23]. The mathematical problem of optimizing the operation of an energy system composed of CHP units, solar thermal modules and DHN has to be generally regarded as a variational calculus problem, because the optimization variables expressing partial load operation of each CHP engine are time dependent. However, a MILP formulation of the problem can provide a realistic description of the system by properly discretizing the load curves (in each time interval the thermal and the electrical demands are assumed to be constant) and approximating performance map of components with a set of linear functions [24,25]. The thermal losses along pipelines have been approximated as a fixed percentage of the thermal energy transferred in each time interval. All other relations that describe the system (energy balances, load limits, cost of energy vectors) are intrinsically linear and they do not need to be approximated. A detailed description of the model and the approximation introduced with the linearization of the performance curves can be seen in [26].

The optimization of an energy supply system begins with the definition of the superstructure. It must include all components that can be potentially part of the optimal solution, so that it depends on the specific application case. After the optimization process, the superstructure will be reduced to the optimal configuration.

Fig. 1 shows the system superstructure. The distributed energy system has to supply the thermal and electrical energy required by a set of users. The electric energy can be produced by the CHP systems installed in each production unit, or purchased from the electric grid. The thermal energy can be produced by the CHP systems, by conventional boilers or by a large centralized solar plant. All users can be connected to each other and to the solar field by a district heating network. Additionally, the superstructure includes also a hot water storage.

Many large scale solar district heating systems have been already built in central and northern Europe, mainly in Sweden, Denmark, The Netherlands, Germany and Austria [27]. They consist of ground mounted collector fields integrated into a DHN for supplying heat to residential and industrial areas. The sizes of those plants allow lower specific investments compared to small applications. When the system is coupled with a heat storage, it is possible to reach a solar fraction of approximately 50% [28].

In the superstructure, a typical user *k* can be equipped with a CHP unit and a boiler. The central production unit includes a boiler and a solar field. The district heating network connects the users to one another and to the heat storage. The model is completely general and it can be applied to different applications with a similar superstructure, by changing only the values that describe the components. In the MILP model binary variables have been used for properly describing the choice of centralized/decentralized components inside the system superstructure, as well as the on/off operation of chosen components in the optimal operation strategy.

2.1. Decision variables

The optimization procedure finds the set of decision variables, both binary and continuous, that allow the minimization of the objective function. The identified decision variables are:

- Existence and size of each component;
- Operation status and load level of each component in each time interval;
- Electricity to be exchanged with the electricity network;
- Thermal flows inside the district heating network;
- Size of the thermal energy storage;
- Level of the thermal energy stored in the storage.

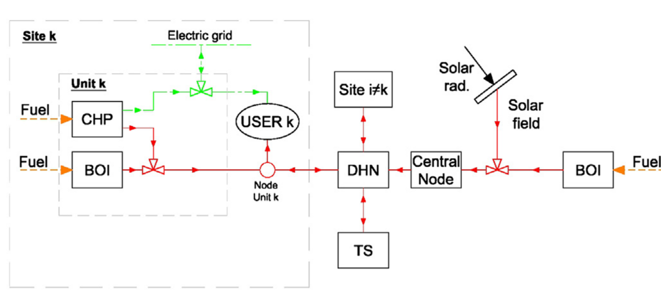

Fig. 1. Superstructure of the energy supply system described by the optimization model.

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