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Optimal synthesis and operation of advanced energy supply systems for standard and domotic home

Dario Buoro [a], Melchiorre Casisi [a], Piero Pinamonti [a], Mauro Reini [b,*]

[a] University of Udine, Electrical, Management and Mechanical Engineering Dept., Via delle Scienze, 208 - 33100 Udine, Italy
[b] University of Trieste, Dept. of Engineering and Architecture, P.le Europa, 1 - 34127 Trieste, Italy

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ABSTRACT

The paper deals with the optimization of an advanced energy supply systems for two dwellings: a standard home and an advanced domotic home, where some demand side energy saving strategies have been implemented. In both cases the optimal synthesis, design and operation of the whole energy supply system have been obtained and a sensitivity analysis has been performed, by introducing different economic constraints.

The optimization model is based on a Mixed Integer Linear Program (MILP) and includes different kinds of small-scale cogenerators, geothermal heat pumps, boilers, heat storages, solar thermal and photovoltaic panels. In addition, absorption machines, supplied with cogenerated heat, can be used instead of conventional electrical chiller to face the cooling demand. The aim of the analysis is to address the question if advanced demand strategies and supply strategies have to be regarded as alternatives, or if they have to be simultaneously applied, in order to obtain the maximum energy and economic benefit.

1. Introduction

The gradual change toward a service economy and new installations for thermal comfort are considerably increasing the energy consumption and emissions of buildings. According to the European Union (EU) Directive on Energy Performances of Buildings [1], the residential sector is generally regarded as responsible for about 40% of primary energy consumption, while its energy saving potential is estimated in the range 20–80%, depending on the accepted technological and economic effort [2,3]. There are two possible energy saving options: demand side and supply side strategies.

Conventional demand side energy saving strategies consist in replacing existent components and technologies with others of the same kind, but with higher energy performance [4]. For instance, increasing wall thermal insulation, or adopting high efficiency electrical lamps and domestic appliances with reduced consumption. In these cases the expected energy saving can be easily evaluated through the consumption reduction ratio that is claimed by the component sellers [5]. On the other hand, advanced demand side strategies can be defined, but they require an automatic intelligent management of energy consuming devices, which can be adopted in the frame of a domotic home. In fact, a home automation system would be able to shut off (or modulate) all energy consuming devices (heating, cooling and lighting), whose operation is not necessary at the moment, taking into account actual environmental condition, comfort set points and human presence [6–8]. Furthermore, it could manage the domestic appliances in order to minimize their consumption when electrical energy is less available, or more expensive. For this kind of energy saving strategies, very few data are available in the literature and a proper evaluation of potential saving would require a simulation of the whole building, in different environmental and usage conditions [9].

Supply side strategies imply the usage of devices that are not usually included in the technical plants of dwellings, like heat pumps, cogenerators, absorption machines, or solar systems, so that the all (or a big part of) required energy can be produced locally [10]. In this case, an actual energy saving can be obtained only if the optimal solutions are adopted for the synthesis (choice of components and technologies), the design (choice of component sizes and investments) and the operation of the whole energy supply system, taking also into account the energy demand variations along with the time of the day and the day of the year [11–13].

The energy supply system for residential home located in Europe is traditionally composed of a boiler for the thermal energy production, a refrigeration chiller for satisfying the cooling demand while the electricity is bought form the electrical grid. Differently, supply system for residential home located in United States substitutes boilers and chillers with heat pumps because the latter have lower investment costs taking also into account that the natural

* Corresponding author.
E-mail addresses: dario.buoro@uniud.it (D. Buoro), melchiorre.casisi@uniud.it (M. Casisi), piero.pinamonti@uniud.it (P. Pinamonti), mauro.reini@units.it (M. Reini).

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Nomenclature

COOLDEM	cooling demand of the user (kW_c)
DQ_{store}	heating power supplied/absorbed by the hot storage (kW_t)
DR_{store}	cooling power supplied/absorbed by the cold storage (kW_c)
E_{in}	electric power supplied to the user agreeing with net metering (kW_e)
E_{cog}	electric power required by the compression chiller (kW_e)
E_{comp}	electric power required by the compression chiller (kW_e)
E_{hp}	electric power required by the heat pump (kW_e)
E_{buy}	electric power bought from the grid (kW_e)
ELDEM	electric demand of the user (kW_e)
E_{pv}	electric power supplied by photovoltaic panels (kW_e)
E_{out}	electric power sent to the electric grid agreeing with net metering (kW_e)
Q_{abs}	heating power required by the absorption chiller (kW_t)
Q_{boi}	heating power supplied by the boiler (kW_t)
Q_{cog}	cogenerated heating power (kW_t)
Q_{hp}	heating power supplied by the heat pump (kW_t)
Q_{st}	heating power supplied by the thermal solar panels (kW_t)
Q_{was}	wasted heating power (kW_t)
R_{abs}	cooling power supplied by the absorption chiller (kW_c)
R_{comp}	cooling power supplied by the compression chiller (kW_c)
R_{hp}	cooling power supplied by the heat pump (kW_c)
R_{was}	wasted cooling power (kW_c)
THDEM	heat demand of the user (kW_c)

gas distribution grid is not widespread. In the current market scenario, where energy prices trend is always increasing together with the pollutant emissions, it is necessary to reduce the primary energy requirement acting in the efficiency, improving energy supply systems and reducing the energy demand. Recently, some works concerning the optimization of CHP systems for residential home, carried out by Ren and Gao [14] and by Shaneb et al. [15], show that micro CHP systems are convenient from both economical and environmental points of view. Alanne et al. [16] and Favrat et al. [17] proposed two multi-criteria evaluation methods for helping the choice of the best configuration of the energy supply system considering the uncertainty [16] and various component kinds [17]. Optimization-based selection approaches have been proposed to select building shapes [18,19], wall and roof constructions and insulation levels [20,21], or several other building envelope design features [22,23], while Bonino et al. modeled and simulated an Intelligent Domotic Environment [8,9].

In this context, the present research wants to mix together the energy supply system optimization approach with the demand side energy reduction approach, in order to understand how they can be put together and if they have to be applied simultaneously to achieve the best results in terms of economical and environmental benefits.

This paper proposes an optimization model for the energy supply system of residential home which has been used for the optimization of two dwellings: a standard home and an advanced domotic home, where some demand side energy saving strategies are supposed to be implemented. In both cases the optimal synthesis, design and operation of the whole energy supply systems have been obtained and a sensitivity analysis has been performed, by introducing different economic constraints.

The optimization model is based on a Mixed Integer Linear Program (MILP) following a similar approach to other work present in the literature [24–26]. The model presented in this paper includes different kinds of small-scale cogenerators, geothermal heat pumps, boilers, heat storages, solar thermal and photovoltaic panels. In addition, absorption machines, supplied with cogenerated heat, can be used instead of conventional electrical chiller to face the cooling demand. The optimal solution has to specify the kind, the size and the connections among components, as well as the optimal operation of the whole system. Two sets of binary variables are used to express the adoption/rejection of each potential component, inside a properly defined superstructure, and the operating/not operating condition of each adopted component, in a particular moment. The aim of the analysis is to address the question if advanced demand strategies and supply strategies have to be regarded as alternatives, or if they have to be simultaneously applied, in order to obtain the maximum energy and economic benefit. In previous papers of the same research group, energy systems operation and optimization have been studied, focusing distributed cogeneration systems integrated with district heating network [27–29], analyzing how different support policies affect the adoption of integrating renewable energy sources [30], and introducing the optimization of trigeneration systems, integrated with district heating and cooling network [31,32]. In the present paper, a similar methodology is applied to the evaluation of possible energy and economic savings at the level of individual residential dwellings.

2. Standard and domotic home

The term "domotic" derives from the latin word "domus". It refers to the automation of the various facilities of the house and the application of automation techniques for the comfort and security of its dwellers, and it is also known as "home automation". For that, domotics can be applied to innumerable tasks and what really contributes at the degree of automation is the level of comfort that wants to be reach. Depending on the technological and economical level, the functions carried out by the domotic system can change widely [33,34].

From the demand side, domotic systems can control lights, blinds, and awnings, adjusting them automatically to the intensity of light throughout the day [6,7]. They can even control the automatic turning on and off of the lights in passageways when someone goes through them, they can manage domestic appliances (dishwasher or washing machine) and the temperature of the dwelling, both the systems of air conditioning and heating, based on the weather conditions which affect the comfort inside the house. They can also control anti-burglar alarm systems, fire alarms, water leakage alarms, gas escapes, etc., but these kinds of control do not affect the energy consumption of the house and they are not taken into account in this work.

From the supply side, the domotic system controls the operation of each component of the heating and cooling central, based on the weather conditions and on the market prices of gas and electric energy. The system allows to meet the energy demands of the user with the least expense. The home then uses a set of optimization algorithms to simultaneously maximize savings and comfort by automatically controlling the HVAC systems, windows,