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Optimal allocation of thermal, electric and cooling loads among generation technologies in household applications

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HIGHLIGHTS

- Minimization by means of a genetic algorithm of the annual flux of primary energy.
- CHP can represent an option only for efficiencies higher than a threshold value.
- The threshold value depends on integrated energy system characteristics.

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ABSTRACT

The legislation of various European countries imposes limits on the demand for building heating and cooling in order to reduce the primary energy consumptions. Moreover, the legislation prescribes that a fraction of the demand for building cooling, heating and power must be met through renewable energy sources. Among renewable energy systems, wind power, solar photovoltaic, solar thermal energy, solar cooling and heat pumps (though only "partially" renewable) have to be mentioned. In this framework combined heat and power (CHP) systems can provide a further solution to reduce the primary energy consumption.

Due to the availability of different technologies, a key factor is the choice of the allocation strategy which allows the division of the energy demands among the various technologies in order to minimize the primary energy consumption. Since the cost of the technologies and the actual tariff and incentive scenarios depend on the specific country and may lead to not optimal allocation strategies in terms of primary energy consumption, these economic parameters are not taken into consideration in the analysis. Therefore, the obtained solutions represent a target which the policies should aim to achieve.

This paper aims to develop and apply a methodology for the optimal allocation of the demand among CHP and renewable energy systems, with the aim of minimizing the primary energy consumption, by accounting for legislative constraints.

The methodology is then applied to different climatic scenarios to evaluate the effects of a variation of the demand and technology characteristics on the allocation of the loads. Moreover, an analysis on the combined effects is presented. Finally, some guidelines are obtained.

1. Introduction

In recent years, governments of most nations around the world have pledged to (i) limit carbon dioxide emissions, (ii) reduce primary energy consumption through an increase of efficiency in production, distribution and end-use and (iii) increase the utilization of renewable energy sources. In general, these goals are pursued separately by law, by subsidizing renewable energy technologies (e.g. photovoltaic panels [1]), the reduction of the demand (e.g. through residential building renovation [2]) or the use of high efficiency technologies for energy production or end-use [3].

These non-coordinated policies may result in an obstacle to the achievement of the optimal integrated energy system configuration, in particular in the household sector, since they may distort the demands (electric, thermal and cooling energy) both in terms of absolute amounts and relative distributions.

Current condensing boilers for residential dwellings reach a very high thermal efficiency [4], but can only meet the thermal demand. Other options for thermal demand fulfillment are electric driven or absorption heat pumps [5,6] and solar collectors [7]. The electric demand is usually taken from the electric grid or partially met by photovoltaic panels [8].

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Nomenclature

Symbols

C	ratio of electric and thermal energy
COP	coefficient of performance, i.e. ratio of the heating produced over the electric or thermal energy consumed
D	demand
E	electric energy
EER	energy efficiency ratio,i.e. ratio of the cooling produced over the electric or thermal energy consumed
f_μ	auxiliary function
N_G	net exchange of electric energy with the grid
PE	primary energy
Q	thermal energy
R	irradiation
S	panel surface
TH	solar thermal collector
x	optimization variable
δ	duration of the period
η	efficiency
μ	penalty parameter

Subscripts

I	overall efficiency
ac	absorption chiller
a&l	appliances and lighting
boiler	boiler
c	cooling
cc	electric compression chiller
CHP	combined heat and power
el	electric energy
G	electric grid
HP	heat pump
ms	mid-season
PV	photovoltaic panel
s	summer
stc	solar thermal collector
th	thermal
tot	total
w	winter

Acronyms

CHP	combined heat and power
HP	heat pump
LCA	life cycle assessment
PV	photovoltaic

A possible further development can be the diffusion of micro combined heat and power systems [9,10], which allow the thermal demand to be met and simultaneously produce electricity that can be self-consumed within the dwelling. In the framework of a distributed generation strategy, CHP systems can potentially provide a higher fuel utilization factor and, therefore, a reduction in the overall consumption of primary energy.

Cooling energy demand can be met by using electric chillers (i.e. the cooling energy is converted into an additional electric load) or absorption chillers (i.e. the cooling energy is converted into an additional thermal load) [11].

Moreover, hybrid systems which combine two or more of the previously mentioned systems have been also conceived [12–16].

In such a scenario of available energy sources (both fossil and renewable) and technologies, it is necessary to define methods and guidelines that help to optimally configure and manage a complex system. This system comprises a plurality of different generation technologies, utilities and energy sources, in order to optimize the exploitation of fossil and renewable sources in terms of environmental impact and economic performance [17,18]. Regarding this topic, in recent years, several authors have proposed optimization models for cost reduction [19], emissions reduction [20], energy planning at regional or global level [21], demand definition and forecasting [22], definition of management strategies [23] and the multi-objective optimization of the configuration and management of a complex system [24,25].

These analyses are usually applied to a large-medium scale, but some examples of the application to a small scale case, such as households, are reported in literature. In [26] an optimization algorithm is applied in order to appropriately design and operate a grid-connected PV panels-Diesel engine-storage energy system. Moreover, the analysis takes into consideration the electric load only.

A comprehensive analysis which takes into consideration all the demands (electric, thermal and cooling) of a residential user is presented in [9]. In this work, the effect of the thermal energy storage size is evaluated for a grid connected integrated energy system composed of a CHP system, an auxiliary boiler and a heat storage (none of the renewable energy systems are taken into consideration). In [27] the focus is the optimal sizing of the CHP system. In [28] a micro-CHP system is compared to traditional heating systems through a multi-criteria evaluation that accounts for: (i) the decision-makers' subjective preferences, (ii) uncertainties in the performance of micro-CHP systems and (iii) the context-dependency of life-cycle costs and environmental burdens of heating systems.

In [29] a multi-criteria approach is applied to integrated energy systems using renewable energy systems (solar collectors, solar photovoltaic panels, wood boilers, geothermal heat pumps) and a gas boiler heating system in order to find the optimum solution based on criteria like CO_2 emissions, costs and energy consumption.

The paper [30] presents the optimization model based on a genetic algorithm of a combined cooling, heat and power system. The influences of the technical, economic and environmental parameters on the optimal results are analyzed and compared numerically. Some guidelines for the optimal design of the combined cooling, heat and power system are reported.

In this framework, the aim of the present paper is to develop a methodology based on the minimization by means of a genetic algorithm of the annual flux of primary energy (i.e. the LCA of the whole energy system is not taken into consideration). This methodology is then applied to a household case. The minimization is performed by varying the load allocation among the different generation technologies for a fixed energy demand. The effect of demand characteristics and technology parameters are evaluated one by one and concurrently for three different climatic scenarios in order to draw some general rules of thumb. Since economic parameters are not considered in the analysis, the results are general and can be used to orient the policies (e.g. incentives) in order to achieve the minimization of the primary energy consumption. Minimizing the annual flux of primary energy, at a given energy demand, also implies a reduction of carbon dioxide emissions, thus moving towards the goals of climate forcing legislation.