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Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application

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HIGHLIGHTS

- The profitability of micro-CHP systems for residential application is investigated.
- The system comprises: prime mover, electric/thermal storage and auxiliary boiler.
- A ZEBRA electrochemical storage is considered, requiring also thermal energy.
- Prime movers could be conventional or innovative systems, i.e. ICE, fuel cell or ORC.
- An in-house developed calculation code is used, performing thermo-economic analysis.

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ABSTRACT

The aim of this paper is the evaluation of the profitability of micro-CHP systems for residential application. An integrated CHP system composed of a prime mover, an Electric Energy Storage system, a thermal storage system and an auxiliary boiler has been considered. The study has been carried out taking into account a particular electrochemical storage system which requires also thermal energy, during its operation, for a better exploitation of the residual heat discharged by the prime mover. The prime mover could be a conventional Internal Combustion Engine or also an innovative system, such as fuel cell or organic Rankine cycle.

An investigation of this integrated CHP system has been carried out, by means of an in-house developed calculation code, performing a thermo-economic analysis. This paper provides useful results, in order to define the optimum sizing of components of the integrated CHP system under investigation; the developed code allows also to evaluate the profitability and the primary energy saving with respect to the separate production of electricity and heat.

1. Introduction

Among the approaches to achieve the targets of primary energy saving and greenhouse gas reduction [1], combined heat and power (CHP) generation is a feasible strategy, recognized and supported by the European Union [2]. The potential and actual convenience of CHP systems strongly depends on the specific techno-economic scenario in which the CHP system operates. Several studies can be found in literature concerning the assessment of CHP advantages–disadvantages from the energy/environmental/economic points of view and in various applications [3–12]. The analyses carried out here refer to the case of a residential building application and to a typical Italian economic tariff scenario, but the methodology could be extended to other market scenarios.

The applications of CHP technologies to the residential sector is still limited and, as pointed out in a previous study of the authors [13], the correct sizing of components is a critical aspect which should be properly defined, in order to maximize the system profitability and energy saving. In particular, among the key factors affecting the CHP profitability, a proper management of the energy flows between the prime mover and the storage subsystems should be considered. In the previous study [13], an investigation had been carried out by considering the external electric net as the only available system to store in the surplus of electric energy and to withdraw from the additional requested power. In this study, the presence of an additional electrochemical battery working as Electric Energy Storage system (EES) is considered. The EES helps to decouple the production and utilization of electricity and it is useful in the energy systems in which at least one of the following conditions occurs:

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Nomenclature

Abbreviation

CHP	combined heat and power
EES	Electric Energy Storage system
FC	fuel cell system
ICE	Internal Combustion Engine
LHV	fuel lower heating value
MGT	Micro Gas Turbine
MRC	Micro Rankine Cycle
STL	stirling
TES	Thermal Energy Storage system
ZEBRA	Zero Emission Battery Research Activity

Symbols

C	electric to thermal energy ratio
D	energy demand (kW h)
E	energy (kW h)
I	current intensity (A)
j	j-th time interval
P	power (kW)
PB	payback period (year)
PD	power demand (kW)
p	transformation/transmission loss coeff. (–)
PEC	Primary Energy Consumption (kW h)
PED	Primary Energy Demand of user (kW h)
SPE	saving of primary energy (–)
V	voltage (V)
Z	number of ZEBRA modules (–)
η	efficiency (–)

Subscript

boiler	auxiliary boiler
CHP	combined heat and power
el	electric
net	electric network
purchased	purchased energy
ref	reference
sold	sold energy
stored	stored energy
th	thermal
U	utilization

- The electricity production prediction is limited by external non-programmable conditions (e.g., availability of renewable source energy systems, such as wind or solar energy).
- The external electric network is not available, or with limited capacity.
- The power generator operates at fixed point and at full power, to respect the maximum efficiency conditions, or for other reasons linked with the generator characteristics (e.g., in high temperature fuel cells, the large internal thermal inertia do not allow the system to comply with rapid load changes).
- The electric power requested by the utilities undergoes rapid and strong changes due to its stochastic components and the power generator can hardly follow the fluctuating request.

Moreover, the electric energy request is usually not directly correlated with the thermal energy request. Thus, also a Thermal Energy Storage system (TES) can be used in a CHP system, in order to store the available thermal energy not absorbed by the utilities during the operating periods in which thermal surplus occurs, instead of dissipating it, with the aim to increase the primary energy saving. In the preliminary study [13] the TES minimum size had been linked to the CHP prime mover power size and the thermal user request. Results of the previous study concerning the TES sizing will be used also within this paper.

More in general, the sizing of both the EES and the TES is affected by the user energy request versus time profiles, by the size of the prime mover and by the electricity tariffs, as it is shown in this paper. In the first section, the considered CHP system layout is described, taking into account the available, developed or under development, technologies for prime movers and for electricity storage devices; in the following section, the methodology of the carried out analysis is introduced, describing the user scenario and the used CHP generators and electrochemical batteries taken into consideration as EES. Finally, the obtained results are shown and a critical analysis is carried out.

2. The considered CHP system layout

The integrated CHP system under investigation is presented in Fig. 1 which shows a visual representation of the main components and possible exchanges of electric and thermal energy considered in this study (the figure is a screenshot of the in-house developed calculation code used for this study and the shown energy numbers correspond to one possible operating condition). This system, aimed at fulfilling the electric and thermal energy requests of a residential building, comprises: (i) a CHP prime mover subsystem, (ii) an EES device, (iii) an external electric network, (iv) an auxiliary boiler and (v) a TES device.

2.1. CHP prime mover subsystems for residential applications

The CHP prime movers suitable for residential application are rated for electric power values ranging typically between 1 kW (or even less in some cases) and 10 kW. Values of electric efficiency and thermal efficiency (calculated with reference to fuel LHV) of commercial Internal Combustion Engines (ICEs), Micro Gas Turbines (MGTs), Micro Rankine Cycles (MRCs) and Stirling engines (STLs) are reported in Fig. 2, as provided by different manufactures and also shown in [13]. Lines of constant electric to thermal ratio (C factor) and lines of constant utilization factor (η_U), sum of electric and thermal efficiency, are also plotted. In such applications, maximum values of η_U could be close to 100% in case of recovery of a large part of the condensation heat in the prime mover exhaust gases.

2.2. EES for residential applications

The electric energy generated by the CHP prime mover can be stored in an electrochemical storage device, while other EES technologies, such as flywheel, supercapacitors, hydrogen or water reservoirs, and compressed air which can be feasible in other applications and could be considered in general terms, are not taken into account here for size and commercial availability issues and for sake of simplicity. Fig. 3 shows, according to [14], the typical performance, in terms of power density and energy density, of different families of electrochemical batteries, characterized by different chemical composition of the electrolytes: conventional lead acid, Ni–Cd, Ni–Metal hydride, and Lithium Ion, with increasing capacity per mass and costs, and finally the ZEBRA (Zero Emission Battery Research Activity), whose working principle is described in