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Minimization of the Primary Energy Consumption of Residential Users Connected by means of an Energy Grid

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Abstract. In this paper, a physics-based model is developed to simulate the interaction between residential users and energy systems. The simulation model is coupled with a dynamic programming algorithm which identifies the optimal operation strategy that allows the minimization of the primary energy consumption of three residential users, arranged with different energy system configurations. The reference scenario, which considers that the users employ a domestic boiler for meeting thermal energy demand, while electric energy is taken from the national electric grid, is compared to the CHP scenario, this latter being differentiated by considering shared thermal and electric energy storages and also shared PM. The most suitable energy system configuration is identified by jointly evaluating primary energy consumption, prime mover working hours and thermal and electric energy share of the prime mover itself.

INTRODUCTION

In the literature, the suitability of CHP (Combined Heat and Power) systems to the residential sector is one of the most investigated topics [1]. One of the main reasons of this interest is due to the fact that approximately the 40% of total energy consumption is used for building heating [2]. Thus, CHP units for domestic applications could represent a strategic alternative to boost primary energy saving in dwellings. In this "CHP scenario", both thermal and electric energy is supplied by a prime mover (PM). One of the key aspects to improve saving is the optimization of PM operation.

Dynamic programming (DP), developed by Bellman in [3], is one of the optimization strategies that has consolidated in the energy system area in the last years [4]. DP allows to handle decision-making problems by means of the minimization or maximization of a given objective function, providing the global minimum thanks to the Bellman's optimality principle.

In the literature, DP models are exploited to solve different decision-making problems (e.g. minimizations of losses, emissions, risks or costs) and several studies [4-7] also applied DP models to residential user applications. For example, DP is applied in [4] to a biofuel micro CHP system with the aim of identifying the optimal power distribution for CHP suppliers. DP was also validated in the study [5], where it was employed to evaluate the optimal control strategy to minimize the primary energy consumption in a building case study. An optimization model based on DP was developed in [6] to evaluate the economic dispatch problem related to a micro-gas turbine coupled with a CHP system. The benefits and viability of the energy system was examined on four different residential scenarios. Finally, the DP algorithm was used in [7] to investigate the feasibility of integrating a power sink in a residential micro-CHP system. As a result, the DP algorithm was able to identify the control strategy which minimized the operating costs.

In this paper, three energy system configurations, i.e. (1) reference scenario, (2) shared TES and electric energy storage (EES) and (3) shared TES, EES and PM, are evaluated and discussed. Three residential users are considered. In the "reference scenario", each residential user is equipped with a domestic auxiliary boiler (AB) for meeting thermal energy demand, while electric energy is taken from the national electric grid (EG). The "shared TES and EES" configuration considers that each user is equipped with its own PM, AB and is connected to the EG. Unlike the previous configuration, one TES and one EES are shared among the three users; thus, the TES also plays the role of a DHG. The last configuration, named "shared TES, EES and PM", is similar to the one with shared TES and EES, but only one PM is used to meet the demand of both users.

A physics-based simulation model is developed in this paper for replicating the interaction of the energy systems and the users. The operation strategy of the PMs is optimized by means of a computational tool, based on DP. The

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objective function to be minimized is the primary energy required to meet the thermal and electric energy demands, which are taken from the literature and mimic a winter day of a typical residential user.

The main novel feature of this paper is that, thanks to the general user configurations, a free optimization strategy is investigated by means of the DP algorithm. Thus, the AB and the connection with the EG can be always exploited by the users and not only during peak hours. In addition, the optimization strategy also accounts for different sizes of both the TES and the EES. Finally, the contribution of an energy grid connecting the residential users is investigated.

METHODOLOGY

The main components of the energy systems considered in this paper are the PM, the EES and the TES. A back-up system for electric energy supply, composed of an AB and the EG, is also available. Finally, a DHG is also present, to supply thermal energy in case of need.

In this study, thermal and electric energy demands are met by following a control strategy that uses both the PM and the back-up systems. This means that the optimization algorithm selects the most suitable strategy for switching on/off the PM or the AB (either simultaneously or alternatively). The goal to be achieved is the minimization of the primary energy consumption.

Energy System Modeling

The State of Charge (SOC) of a TES at time point (t+1) accounts for the SOC at time t and the thermal power P_{TES} entering/leaving the TES. Moreover, it also accounts for thermal leakage, by means of a thermal leakage rate, defined according to [8]. The SOC is thus estimated according to Eq. (1):

$$SOC_{TES}^{t+1} = (1 - \in_{th}) \cdot (SOC_{TES}^{t} - P_{TES} \cdot \Delta t) \tag{1}$$

The thermal power P_{TES} can be expressed as in Eq. (2):

$$P_{TES} = \sum_{i=1}^{n_{user}} \left(P_{th,user,i} - u_i \cdot P_{th,max} - P_{th,AB,i} \pm P_{th,DHG} \right) \tag{2}$$

where P_{TES}, i.e. the thermal power entering or leaving the TES, depends on the thermal demand of the user $P_{th,user}$, and the thermal power supplied by the PM, the AB and by the district heating, $P_{th,DHG}$. This latter term can be either entering or leaving. Moreover, this term is equal to zero in the reference scenario, since the system configuration does not include the DHG.

By neglecting electric energy leakage, the SOC of each EES can be estimated according to Eq. (3):

$$SOC_{EES}^{t+1} = (SOC_{EES}^{t} - P_{EES} \cdot \Delta t) \tag{3}$$

The electric power PEES entering/leaving the EES can be expressed as in Eq. (4), by also accounting for inverter efficiency η_{inv} and EES charging efficiency η_{ch}.

$$P_{EES} = \begin{cases} \dfrac{1}{\eta_{inv}} \cdot \left(\displaystyle\sum_{i=1}^{n_{user}} P_{el,user,i} - u_i \cdot P_{el,max} - P_{el,EG,i}^{+} \right) if \displaystyle\sum_{i=1}^{n_{user}} P_{el,user,i} - u_i \cdot P_{el,max} - P_{el,EG,i}^{+} > 0 \\ \eta_{inv}\eta_{ch} \cdot \left(\displaystyle\sum_{i=1}^{n_{user}} P_{el,user,i} - u_i \cdot P_{el,max} - P_{el,EG,i}^{+} \right) if \displaystyle\sum_{i=1}^{n_{user}} P_{el,user,i} - u_i \cdot P_{el,max} - P_{el,EG,i}^{+} \leq 0 \end{cases} \tag{4}$$

If both conditions expressed in Eq. (5a) are satisfied, i.e. the EES is full and user power demand is lower than the sum of PM power output and electric power taken from the EG,

$$\begin{cases} SOC_{EES} = SOC_{EES,max} \\ \displaystyle\sum_{i=1}^{n_{user}} P_{el,user,i} - u_i \cdot P_{el,max} - P_{el,EG,i}^{+} < 0 \end{cases} \tag{5a}$$

the surplus of electric energy produced by the PM, that cannot be stored in the EES, is sent to the EG according to Eq. (5b):

$$E^{-}_{el,EG} = \left(u \cdot P_{el,max} - P_{el,user}\right) \cdot \Delta t \tag{5b}$$

Objective Function

As previously mentioned, the objective of this study is the minimization of the primary energy consumption, which accounts for the contribution of all the available PMs. Therefore, E_p can be estimated according to Eq. (6):

$$E_p = \left(\sum_{i=1}^{n_{PM}} \frac{u_i \cdot P_{el,max,i}}{\eta_{PM,i}(u_i)} + \frac{P_{th,AB,i}}{\eta_{AB,i}} + \frac{P_{el,EG,i}}{\eta_{EGm} \cdot p} \right) \cdot \Delta t \tag{6}$$

The electric efficiency of each PM, i.e. $\eta_{PM,i}$, is a function of its load u_i, which, in general, is a continuous variable ranging from 0 to 100% (i.e. design point). The auxiliary boiler is considered as a standard non-condensation unit. As discussed in the next section, its efficiency is chosen accordingly. The evaluation of the primary energy used to produce electricity in the national electric grid accounts for its efficiency η_{EG} (this value usually depends on the considered Country and generation technologies which compose the national electric grid) and the losses due to transport and electricity conversion from high to low voltage, by means of the parameter p, which is also Country-related.

Optimization Algorithm

DP is a numerical algorithm based on Bellman's optimality principle [3], which can be used to identify the absolute minimum value of a given objective function while satisfying system constraints. A DP model is a sequential decision process, with two main components, i.e. states and decisions. A state can be represented as a snapshot of the situation at a given time point. It describes the developments in such a manner that alternative courses of action are possible and can be evaluated. A control variable, also called decision, is an action that causes the state to change. Thus, a decision causes a movement from one state to another. The state-transition equations govern the movement. A sequential decision process starts at a given time point and continues until a final state is reached. The DP algorithm, which requires a static and discrete time model of the system, works backward starting from the final time point and goes back to the initial time point. As discussed in [9], the advantages of DP compared to other optimization techniques are (i) its efficiency, (ii) the fact that it is not influenced by the linear or nonlinear nature of the problem and, above all, the capability of always identifying a solution representing the global optimum.

The DP algorithm employed in this paper is implemented in Matlab® environment, based on a routine developed by [10] and publicly available at [11]. The selected states account for the fact that the maximum number of state variables allowed by the DP function available at [11] is five.

CASE STUDY

Energy System Configuration

The case study investigates the most suitable energy system configuration which should be adopted to meet the thermal and electric energy demand of three residential users. Three energy system configurations, i.e. (1) reference scenario, (2) shared TES and EES and (3) shared TES, EES and PM, are evaluated and discussed.

Reference Scenario

In the "reference scenario", shown in Fig. 1, each residential user is equipped with an AB for meeting thermal energy demand, while electric energy is taken from the national EG.

Shared TES and EES

In this configuration, shown in Fig. 2, each user is equipped with its own PM, AB and is connected to the EG. In addition, one TES and one EES are shared among the users; thus, the TES also plays the role of the DHG.

Shared TES, EES and PM

The last configuration, sketched in Fig. 3, is similar to the one with shared TES and EES, but only one PM is used to meet the demand of the three users. This configuration is clearly aimed at taking advantage of peak shaving among the users and increasing the number of PM yearly working hours.

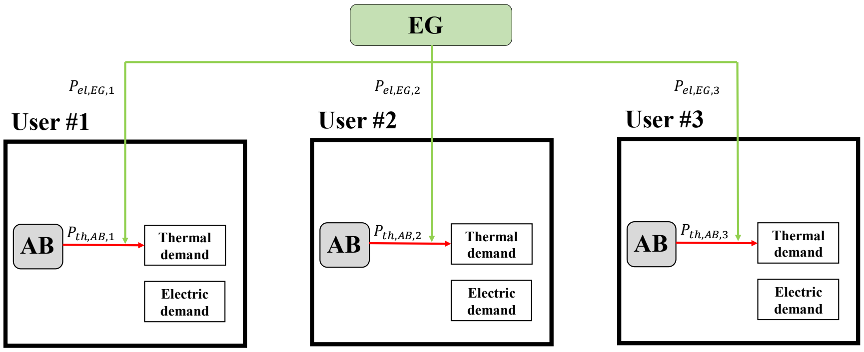


FIGURE 1 – Reference scenario

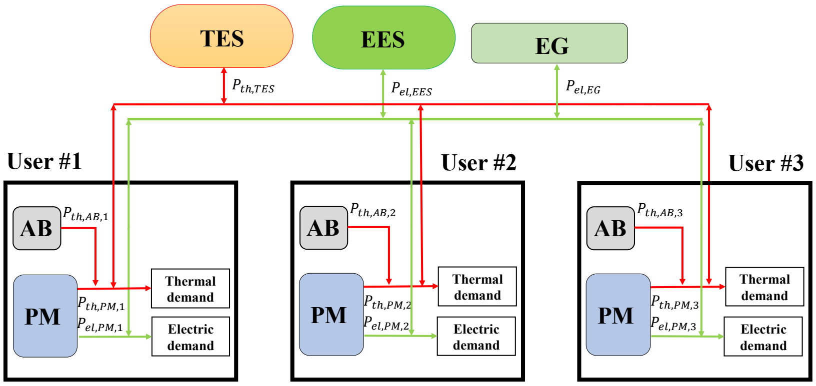


FIGURE 2 – CHP scenario with shared TES and EES

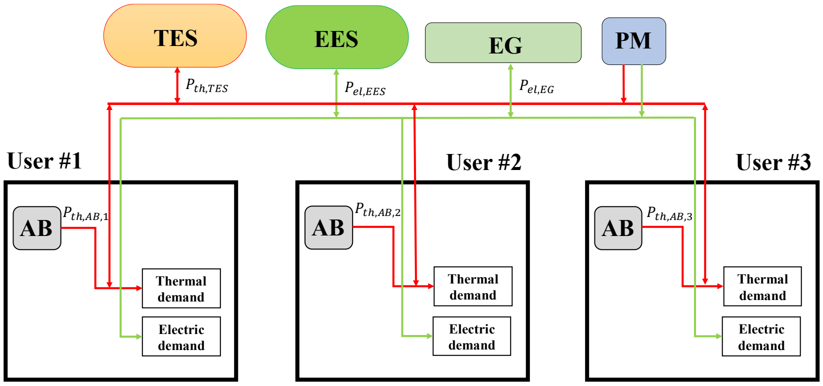


FIGURE 3 – CHP scenario with shared TES, EES and PM

User Energy Demand

The thermal and electric energy demands of the three considered residential users are reported in Fig. 4. The trends represent a typical winter day and are derived from [12]. It should be noted that the trend of user #1 is the same as reported in [12], while small random variations were imposed to simulate the trend of user #2 and #3. Moreover, since each user is supposed to be composed of eight single-family users (e.g. a block of eight flats), the thermal and electric demand is scaled accordingly.

Energy System Components

Prime Mover

Because of its current market availability [13,14], the PM considered in this paper is based on internal combustion engine technology. In particular, the "shared TES and EES" configuration includes two PMs, while the "shared TES, EES and PM" only includes one PM. The electric and thermal power supplied by the considered PM, as well as the electric and thermal efficiency, are assumed in agreement with [15]:

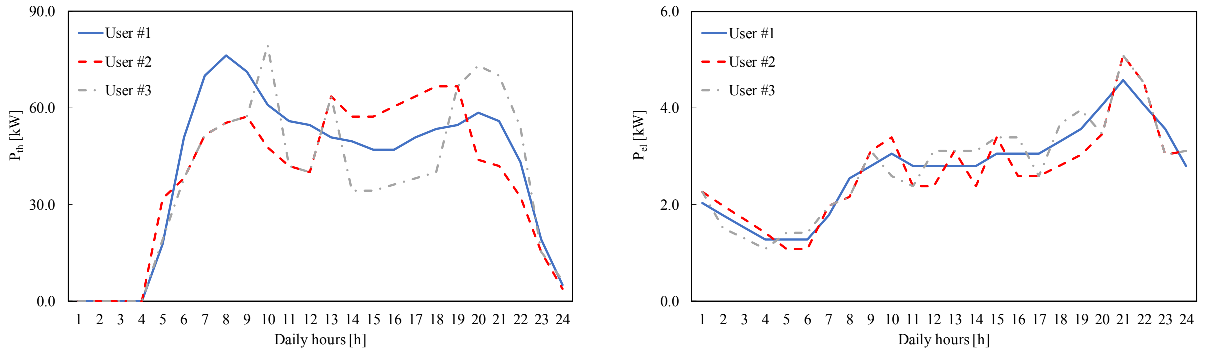
- $P_{el} = 8.50$ kW;
- $P_{th} = 20.10$ kW;
- $\eta_{el} = 0.282$;
- $\eta_{th} = 0.667$.

TES and EES

The capacity of the TES and EES is usually recognized in the literature as a key factor for optimizing the operation of the CHP systems. Therefore, a sensitivity analysis is carried out in this paper on these two capacities, by considering different TES (in the range from 50 kWh to 200 kWh) and EES (in the range from 20 kWh to 50 kWh) sizes. These capacities are in agreement with the selected users and similar applications available in the literature [16].

System Parameters

Some system parameters, as the ones reported in Table 1, are assumed constant. In fact, in general, they represent variables which are imposed by standards (e.g. η_{AB} and p) or depend on national grid (i.e. η_{EG}). Finally, the two parameters η_{inv} and η_{ch} are usually very high and thus, in case they are varied, they slightly affect the final result of the optimization.



(a) (b)

FIGURE 4 – Daily power demand of three users: (a) thermal power, (b) electric power

TABLE 1 – Constant model parameters

Efficiency	Value	Reference
η_{AB}	0.900	[17]
η_{EG}	0.460	[18]
p	0.851	[17]
η_{inv}	0.94	[19]
η_{ch}	0.98	Assumption

Control Variables and States

The considered ranges of variation and discretization adopted for the control variables and states are listed in Table 2. In the analyses, the load u can be equal to 0 (the PM is switched off) or 1 (the PM is switched on and runs at full load). The nominal thermal power of the AB is assumed equal to 24 kW, since, at present, this is a typical value for ABs suitable to residential users in different locations [1-2, 20]. The thermal power exchanged by means of the DHG is equal to PM nominal power output at maximum. Finally, the electric energy purchased from the national electric grid does not exceed the maximum user electric demand.

With regard to the adopted discretization of the control variables (i.e., AB, DHG and EG), as a compromise between accuracy and computational time, five discrete values are considered.

The two states SOC_{TES} and SOC_{EES}, which represent the output of the DP algorithm, are varied in the range from 5% to 95% of the TES and EES nominal capacity, to account for incomplete charge and discharge. These two states are identified by the DP algorithm by means of a continuous function.

Finally, the minimum switch-on time frame of the PM is assumed equal to 30 minutes, as a compromise between computational effort and real-world operation of internal combustion engines.

RESULTS

The time frame considered for the simulations is a winter working week composed of six identical days such as the ones reported in Fig. 4. This time frame also makes the difference between the final SOC value at the end of the simulated time frame and the initial SOC value lower than 1.5%, independently of the considered system configuration and component sizing.

TABLE 2 – Control variables and states

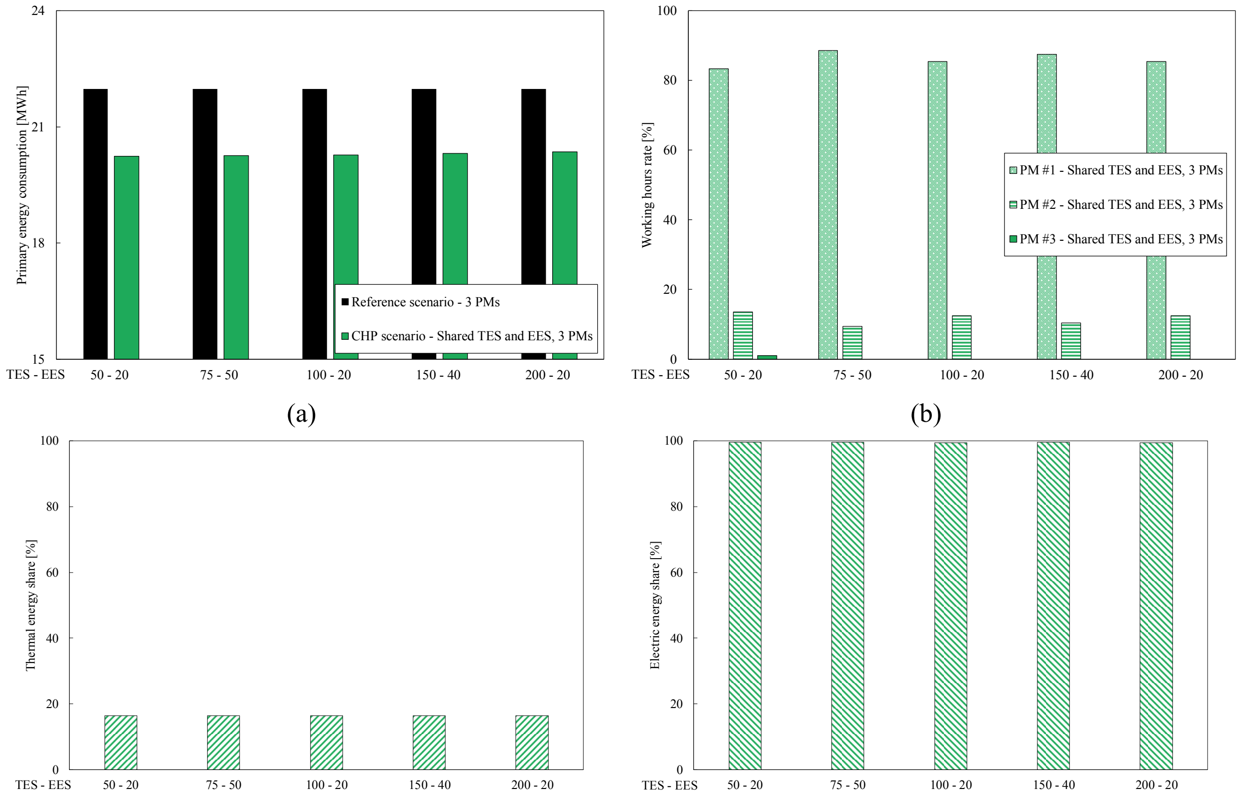
Energy system component	DP component	Variable	Minimum value	Maximum value	Discretization
PM	Control variable	u	0	1	Binary value
AB	Control variable	$P_{th,AB}$	0 kW	24 kW	5 steps
DHG	Control variable	$P_{th,DHG}$	$-P_{th,user,max}$	$+P_{th,user,max}$	5 steps
EG	Control variable	$P_{el,EG}$	0	$+P_{el,user,max}$	5 steps
TES	State	SOC_{TES}	5% $SOC_{TES,max}$	95% $SOC_{TES,max}$	Continuous
EES	State	SOC_{EES}	5% $SOC_{EES,max}$	95% $SOC_{EES,max}$	Continuous

Moreover, it has to be considered that, in both micro-CHP scenarios (i.e. shared TES and EES, shared TES, EES and PM), electric energy can be delivered to the national grid, according to Eq. (5b). Therefore, the primary energy required to produce such electricity is also added to the electric energy produced in the corresponding reference scenario. In this manner, electric and thermal energy production is the same and the different primary energy consumption values can be directly compared.

Figure 5a compares the primary energy consumption in the reference scenario and in the energy system configuration with shared TES and EES. As can be seen, results are in practice independent of the TES and EES sizes. The considered micro-CHP configuration allows to save the 7.5% of the energy consumption with respect to the reference scenario. According to Fig. 5b, PM#1 runs for 83%-89% of the available time (six days in this paper), whereas PM#2 working hours never exceed 14% of the available time. Finally, with the exception with the first TES – EES combination, PM#3 never runs. The thermal energy share (Fig. 5c) and the electric energy share (Fig. 5d) covered by PMs can be up to 16.5% and 99.5%, respectively. Thus, only the 0.5% of the electric power has to be provided by the EG.

According to Fig. 6, the TES and EES capacities do not significantly affect the primary energy consumption, the PM working hours, the thermal and electric energy share. As observed in Fig. 5a, the primary energy saving in the micro-CHP scenario is equal to 7.5% with respect to the reference scenario (Fig. 6a). The shared PM runs for 98% of the available time at maximum (Fig. 6b) and generally covers the 16.0% of the thermal power demand (Fig. 6c) and the 98.1% of the electric power demand on average (Fig. 6d).

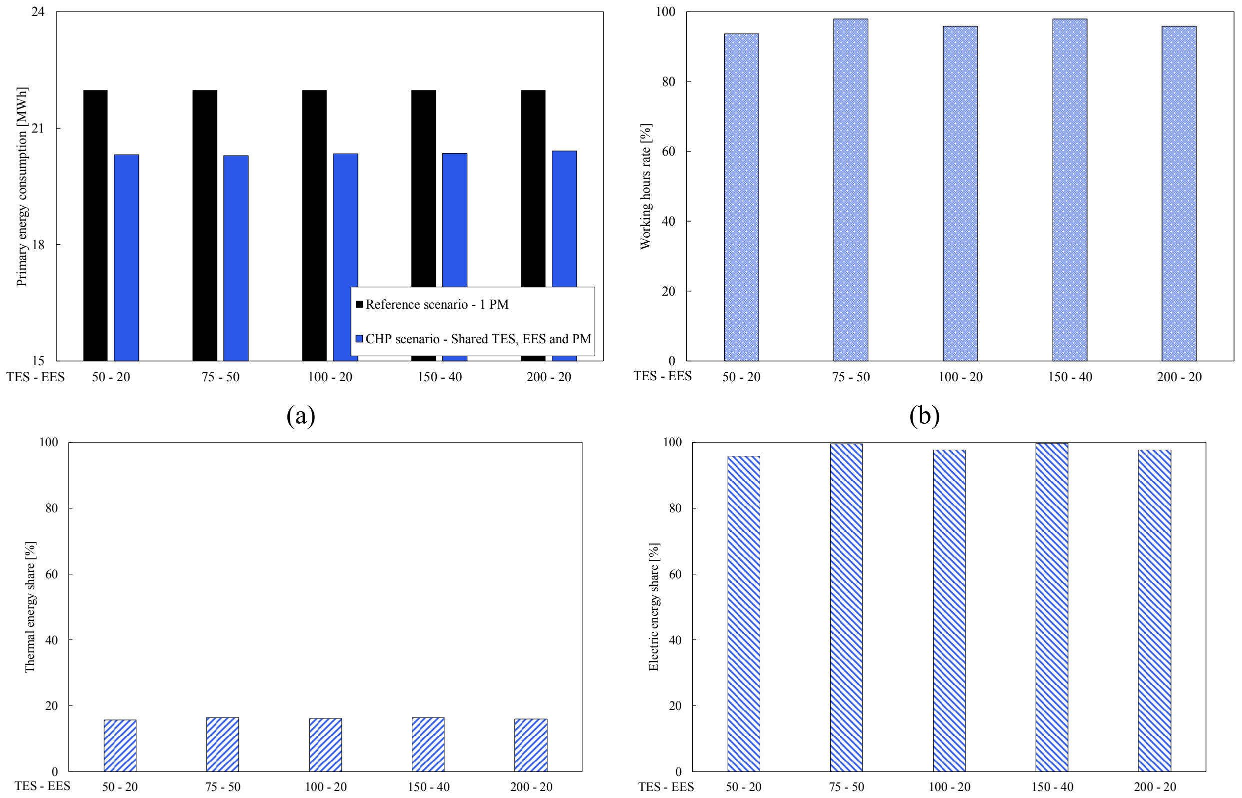
By comparing Fig. 5 and Fig. 6, it is evident that both micro-CHP configurations are generally independent of the TES and EES sizes. Thus, the smallest TES and EES capacities, i.e. 50 kWh and 20 kWh respectively, prove preferable. The energy system configuration with shared TES, EES and PM is preferable, since the primary energy consumption, the thermal and electric energy share are roughly the same, but the shared PM is much more exploited. This clearly allows a significant reduction of energy system costs.



(a) (b)

(c) (d)

FIGURE 5 – Primary energy consumption (a), PM working hours (b), thermal energy share (c) and electric energy share (d) <u>with shared TES and EES</u>



(a) (b)

(c) (d)

FIGURE 6 – Primary energy consumption (a), PM working hours (b), thermal energy share (c) and electric energy share (d) with shared TES, EES and PM

CONCLUSIONS

In this paper, the exploitation of CHP systems in two different configurations (i.e. “shared TES and EES” and “shared TES, EES and PM”), for three residential users and different sizing of TES and EES, was compared to a reference scenario where the users employ a domestic boiler for meeting thermal energy demand and are connected to the national electric grid for meeting the electric energy demand, with the final aim of minimizing the primary energy consumption.

One of the main achievements is that, unlike most studies published in the literature, TES and EES size negligibly affect primary energy consumption in the considered range of values, thanks to the optimized operation strategy identified by means of a dynamic programming algorithm.

In both micro-CHP scenarios, the primary energy saving can be approximately 7.5% with respect to the reference scenario; moreover, the thermal and electric energy share covered by the PM are comparable. Thus, the micro-CHP scenario with a shared TES, EES and PM is suggested, since PM working hours are maximized and energy system installation costs are reduced.

NOMENCLATURE

E	Energy [kWh]	u	Load [%]
p	Parameter which accounts for EG losses	ϵ	Thermal leakage [%]
P	Power [kW]	Δt	Time step [s]
n	Number	η	Efficiency [%]
SOC	State of charge [%]		

Subscripts and Superscripts

+	To the user	el	Electric
-	From the user	inv	Inverter
1	User #1	max	Maximum, Rated
2	User #2	p	Primary
AB	Auxiliary boiler	PM	Prime mover
ch	EES charging	t	Time
DHG	District heating grid	TES	Thermal energy storage
EES	Electric energy storage	th	Thermal
EG	Delivered to or taken from the national electric grid	user	User

Acronyms

AB	Auxiliary boiler	EES	Electric energy storage
CHP	Combined heat and power	EG	Electric grid
DHG	District heating grid	PM	Prime mover
DP	Dynamic programming	TES	Thermal energy storage

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