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Economic assessment of flexibility offered by an optimally controlled hybrid heat pump generator: a case study for residential building

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Abstract

The ongoing decarbonisation process of the current energy system, driven by the EU directives, requires that more renewable energy sources are integrated in the global energy mix, as well as policies promoting investments in new low-carbon technologies, energy efficiency and grid infrastructure. The technical integration of renewable energy sources into the existing power system is not straightforward, due to the intrinsic aleatory characteristics of renewable production, which make the power grid balance harder. To handle this issue, beside the traditional supply-side management, grid flexibility can also be provided by enabling the active participation of the demand-side in power system operational procedures, by means of the so-called demand-side management (DSM). The present paper is aimed at assessing the ability of a cost-optimal control strategy, based on model predictive control, to activate demand-response (DR) actions in a residential building equipped with a hybrid heat pump generator coupled with a water thermal storage. Hourly electricity prices are considered as external signals from the grid driving the demand response actions. It is shown that the thermal energy storage turns out to be an effective way to improve the controller performances and make the system more flexible and able to provide services to the power grid. A daily cost-saving up to 35% and 15% have been highlighted with a 1 m^3 and 0.5 m^3 tanks, respectively. Finally, the achievable flexibility is shown to be strictly dependent on the storage capacity and operations, which in turn are affected by the generators sizing.

Keywords: Flexibility; Demand Side Management (DSM); Model Predictive Control (MPC); Hybrid Heat Pump; Thermal Energy Storage (TES).

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1. Introduction and state of the art

The transition towards a more sustainable energy society requires a new paradigm of the energy system itself. The increasing share of Intermittent Renewable Energy Sources (IRES) poses challenges in terms of grid stability and management which cannot be effectively handled by the traditional power grids [1].In fact, a strong penetration of IRES requires a high grade of energy flexibility at the generation side and at grid level. Beside the traditional supply-side management, grid flexibility can be provided at demand level [2].

The so-called demand-side management (DSM) is an attractive approach consisting of the management of user demand profiles to meet grid requirements, either by increasing or reducing the amount of energy consumed, according to external signals coming from the grid (e.g., hourly electricity prices). DSM programs can be classified either as Incentive-Based Programs (IBP) or Price-Based Programs (PBP) [3]. In the first, customers receive incentive payment in return for the load-reduction provided over a given time period, while in the second one, consumers voluntarily schedule their consumption profiles according to economic signals, such as electricity tariff. Incentives are needed since the variation of the consumption pattern provided by the consumer to support grid operations can lead to higher operational cost for the single end-user.

In this context, buildings play a paramount role since they account for about 40% of the primary energy consumption worldwide [4]. Moreover, the increasing availability of smart metering and control algorithms, which can be used to implement control strategies acting directly on heating, ventilation and air conditioning systems, make buildings suitable for providing DSM [5]. Among the different technologies available to implement demand response (DR) actions, the use of advanced control strategies for the management of electric heat pumps coupled with thermal energy storage appears to be one of the most promising solutions [6, 7, 8].

The present paper is aimed at investigating the flexibility offered by an optimally controlled hybrid generator, consisting of an electrically-driven air-source heat pump and a gas boiler, for residential buildings applications. At first, the impact of a price-based DSM program is investigated in term of consumption patterns and daily operational cost. An optimal control problem (OCP) is solved to determine the control strategy of the generators and the storage tank, in order to meet the load at minimum cost. Then, different scenarios are considered in which the consumer receives a request from the grid for reducing the electrical energy consumption over a given time-period compared with those resulting under the PBP. Hence, the resulting new operational costs are assessed. Since any deviation from the optimal control strategy obtained by solving the OCP will result to be sub-optimal, leading to higher operating costs, the difference between the new operational costs and the benchmark cost relating to the PBP could be used to assess the minimum payout that should be obtained in an IBP. Moreover, the use of a thermal energy storage (TES) and how it affects the end-user operational-cost when a DSM strategy is implemented are investigated.

The following structure is adopted in the present paper: section 2 describes the methodology used to assess the "flexibility cost" associated with different DSM measures. Then, the system modelling and the optimal control problem are presented in sections 3 and 4, respectively. Section 5 describes the case study analysed and section 6 presents and discusses the results obtained. Finally, Section 7 summarises the main findings of the work.

Nomenclature

C	operational cost [€]
c	specific heat [J/kgK]
C_c	degradation coefficient
CR	part-load ratio
E	electrical energy [kWh]
f	part-load correction factor
J	objective function
P	electrical power [kW]
p	price [€/kWh]
Q	thermal energy [kWh]
$\dot{Q}$	thermal power [kW]
T	temperature [^oC]
t	time [s]
$\mathbf{u}$	vector of control variables
V	storage volume [m^3]
$\mathbf{x}$	vector of state variables

Subscripts

B	boiler
em	emission
el	electrical
ext	external
FL	full-load
H	high
HP	heat pump
L	low
PL	part-load
s	storage
th	thermal

Superscripts

Ref	reference
$thld$	treshold

Greek letters

ρ	density [kg/m^3]
η	efficiency
τ	optimisation horizon [h]

2. Methodology

This section describes the methodology used to assess the optimal reference system and the additional cost resulting from a variation in the cost-optimal consumption patterns provided to fulfill a specific request from the grid, as under an IBP. A residential building equipped with an electrically-driven air-source heat pump and a gas boiler was assumed as case study. Two different system configurations are considered as shown in Fig. 1: the first one, with only the hybrid generator and the second one, in which a water tank is added downstream the heat pump in order to decouple energy generation from energy distribution, increasing the flexibility of the system. To assess the "flexibility cost", a bottom-up approach is used [9]. Firstly, a reference case scenario with no DR action is considered and the generators are controlled by means of a model predictive control (MPC) strategy based on an optimal control problem (OCP) solved over on horizon of 24 hours. The resulting daily heating cost, C_{Daily}^{Ref}, is the minimum cost at which the generators can operate to meet the load demand. Any deviation from the optimal control strategy obtained by the MPC will result to be sub-optimal, leading to higher operating costs. As the reference electrical consumption of the heat pump, $P_{HP,el}^{Ref}$, is obtained, several DR actions are implemented based on the electricity price of the day-ahead market: if the price is higher than a selected threshold value, p_{el}^{thld}, the power consumption of the heat pump is decreased of a fixed percentage α until a new target energy consumption, $E_{HP,el}^{target}$ is achieved.

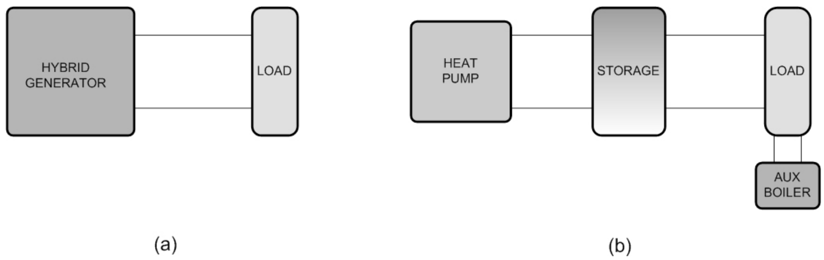

Fig. 1. System Layout: (a) without TES; (b) with TES.

$$E_{HP,el}^{target} = \alpha \cdot E_{HP,el}^{Ref} \tag{1}$$

The threshold value p_{el}^{thld} is defined starting from the maximum and the mean values of the hourly price profile of the day, denoted as p_{el}^{max} and $\bar{p}_{el}$ respectively, and a reduction parameter θ, as shown by Eq. 2.

$$p_{el}^{thld} = \bar{p}_{el}^{max} - \theta \cdot \left(p_{el}^{max} - \bar{p}_{el}\right) \tag{2}$$

By this way, a new optimal control problem is formulated with the aim of minimizing the deviation of the heat pump consumption from the target profile and, at the same time, the operating cost of the system. Different DR actions are considered by varying the value of the parameter and for each of them the daily cost for heating is calculated on the basis of the results obtained by solving the new OCP. A schematic representation of the methodology is shown in Fig. 2.

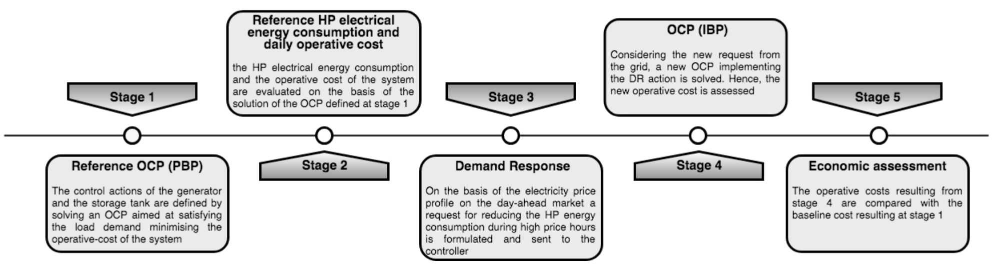

Fig. 2. Schematic view of the adopted methodology.

3. System modelling

An on-off heat pump unit and a gas boiler are considered as components of the hybrid generator. The heat pump coefficient of performance (COP) at full load working conditions, COP_{FL}, is evaluated by means of the second law efficiency, η^{II}, as shown in Eq 3.

$$COP_{FL} = \eta^{II} \cdot COP_{Carnot} = \eta^{II} \cdot \left(\frac{T_H}{T_H - T_L} \right) \tag{3}$$

where COP_{Carnot} is the coefficient of performance of an inverse Carnot cycle operating between the two temperatures T_H and T_L. Then, in order to account for the performance degradation occurring at part-load working conditions, a correction factor, f_{PL}, is introduced according to the standards [10] and [11]:

$$f_{PL} = \frac{CR}{1 - C_c + C_c CR} \tag{4}$$

where C_c is the degradation coefficient, for which, in absence of manufacturer indications, [10] and [11] suggest to use 0.9, while CR is the heat pump part-load ratio, defined as the ratio between the actual delivered power, $\dot{Q}_{HP,th}$, and the heat pump maximum power, $\dot{Q}^{max}_{HP,th}$, as expressed by the following equation:

$$CR = \dot{Q}_{HP,th} / \dot{Q}^{max}_{HP,th} \tag{5}$$

By this way, the COP can be expressed as shown in Eq. 6.

$$COP = COP_{FL} \cdot f_{PL}(CR) \tag{6}$$

The gas boiler is modelled through a constant efficiency, η_B, and the thermal energy storage is considered to be an ideally mixed water tank. Finally, a synthetic building thermal demand profile, $\dot{Q}_{Load,th}$, is evaluated according to the Energy Signature method [12]. The parameters were chosen in such a way that the thermal load reaches the design value, $\dot{Q}^{max}_{Load,th}$, when the external temperature gets to the design outdoor temperature T^{des}_{ext} and becomes zero at the switch-off temperature, T^{off}_{ext}, when building gains and losses are balanced and the heating system is ideally turned off.

$$\dot{Q}_{Load,th} = \dot{Q}^{max}_{Load,th} \cdot \left(1 - \frac{T_{ext} - T^{des}_{ext}}{T^{off}_{ext} - T^{des}_{ext}} \right) \tag{7}$$

4. Optimal Control Problem formulation

The aim of the OCP is to find a control law which satisfies the optimum criterion defined by the cost functional J while meeting a given set of constraints on the overall optimisation horizon, τ. In a very general form the problem can be expressed as follows:

$$\begin{aligned}
&\mathbf{u}^* = arg \min_{\mathbf{u}} J(\mathbf{x}, \mathbf{u}, \tau) \\
&\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}, t) && \forall t \in [0, \tau] \\
&\mathbf{u}^{min} \leq \mathbf{u}(t) \leq \mathbf{u}^{max} && \forall t \in [0, \tau] \\
&\mathbf{x}^{min} \leq \mathbf{x}(t) \leq \mathbf{x}^{max} && \forall t \in [0, \tau]
\end{aligned} \tag{8}$$

The objective functions adopted for the OCP (Eq. 8) is presented and discussed in Section 4.1, while the system dynamics (Eq. 9) and the problem constraints (Eqs. 10-11) are presented in section 4.2.

4.1. Objective function

Considering the array of the control variables, **u**, composed by the thermal power extracted from the storage tank, $\dot{Q}_{s,th}$, the thermal power delivered by the heat pump and by the gas boiler, $\dot{Q}_{B,th}$, the total cost of the reference OCP calculated over the optimisation horizon can be expressed as:

$$J = C_{Daily} = \int_0^{\tau} \left[p_{el}(t) \frac{\dot{Q}_{HP,th}}{COP(t)} + p_{gas} \frac{\dot{Q}_{B,th}}{\eta_B} \right] dt \tag{9}$$

4.2. Constraints

In order to take into account the heat pump and boiler operative ranges, the following relations are considered:

$$\begin{aligned} &\dot{Q}^{min}_{HP,th} \leq \dot{Q}_{HP,th}(t) \leq \dot{Q}^{max}_{HP,th} && \forall t \in [0, \tau] \\ &\dot{Q}^{min}_{B,th} \leq \dot{Q}_{B,th}(t) \leq \dot{Q}^{max}_{B,th} && \forall t \in [0, \tau] \end{aligned} \tag{10}$$

The system is also subjected to the first-order dynamic constraints deriving from the dynamic of the storage tank:

$$\begin{aligned} &V\rho c \frac{dT_s(t)}{dt} = \dot{Q}_{HP,th}(t) - \dot{Q}_{s,th}(t) - \dot{Q}_{loss}(t) \\ &T^{min}_s \leq T_s(t) \leq T^{max}_s \qquad \forall t \in [0, \tau] \end{aligned} \tag{11}$$

Moreover, since the temperature required by the building system (T_{em}) defines the amount of useful energy stored and, consequently, the capacity of the storage to meet the load demand, a further condition is added:

$$\begin{cases} \dot{Q}_{s,th}(t) \geq 0, \; T_s(t) \geq T_{em} \\ \dot{Q}_{s,th}(t) = 0, \; T_s(t) \leq T_{em} \end{cases} \tag{12}$$

By this way, the storage tank is allowed to deliver energy to the load only if its temperature is above the minimum one required by the emission system. Finally, in order to ensure the fulfillment of the building thermal demand at any moment, the following constraint is also added:

$$\dot{Q}_{s,th}(t) + \dot{Q}_{B,th}(t) = \dot{Q}_{Load,th}(t) \qquad \forall t \in [0, \tau] \tag{13}$$

4.3. Modelling tools

The continuous form of the two OCPs described in Section 2 is converted into a non-linear programming problem (NLP) by using a direct collocation technique [13]. The resulting NLP is solved with Python, using CasADI interface to IPOPT. The optimisation horizon is discretised into 24 time-steps, while three collocation points for each step are used.

5. Case study

The presented methodology is applied to a residential building equipped with a hybrid generator composed by an electrically-driven air-source heat pump and a gas boiler, coupled with a water storage tank. The building is considered located in North-eastern Italy, in the city of Trieste. The hourly profile of the external temperature was taken from the Italian Thermo-Technical Committee [14]. The maximum heating load needed by the building is 6 kW with an outside temperature of $T^{des}_{ext} = -1.1^oC$ and a room temperature of 20^oC, while it becomes equal to zero when the external temperature is $T^{off}_{ext} = 20^oC$. The heating system is operated according to the external temperature and occupancy profile: during the occupied period (7 am - 10 pm) the system will turn on if the external temperature is below the switch-off temperature (T^{off}_{ext}), otherwise it will be turned-off. As suggested in [15], the on-off heat pump unit is sized over a fraction of the peak thermal load ($\dot{Q}^{max}_{HP,th} = 4\ kW$) in order to reduce the percentage of time when the heat pump unit works at very low partial-loads, leading to a greater seasonal performance factor (SPF). Moreover, the heat pump can operate only if $T_{ext} \geq 0$, otherwise it is switched-off. Furthermore, in order to fulfill the comfort constraints, the gas boiler is considered able to cover all the thermal power required by the load at any time, at a constant efficiency set equal to $\eta_B = 0.96$. The heat pump coefficient of performance is evaluated considering as T_H the temperature of the storage tank and as T_L the value of external temperature. The emission supply water temperature T_{em} is considered constant and equal to 35 ^oC, typical of radiant heating systems. The second law efficiency is considered constant and equal to $\eta^{II} = 0.35$. The upper and lower bound of the storage tank temperature are set equal to $T^{max}_s = 55\ ^oC$ and $T^{min}_s = T_{ext}$ respectively, while the overall heat transfer coefficient (UA) is considered proportional to the size of the tank: 1.3 W/K for the 0.5 m^3 tank and 2.7 W/K for the 1 m^3 one. Finally, as described in Section 2, demand response strategies are considered according to the hourly values of the electricity prices extracted from the Italian Electricity

Market Operator (EMO) database with regard to the year 2017 [16], while the gas price is considered equal to 8 c€/kWh. The threshold value above which the demand response strategy is activated is calculated considering the reduction parameter θ equal to 0.5 for each day, while different DR actions are considered by varying α, in steps of 0.1, in the range [0.3, 1]. All the simulation runs were performed over the last week of January and the middle-day of the week has been chosen as the reference day on which carrying out the analysis.

6. Results

Fig. 3 shows the optimal control strategy obtained by solving the reference OCP for the two studied configurations: without TES and with the 0.5 m^3 water storage tank.

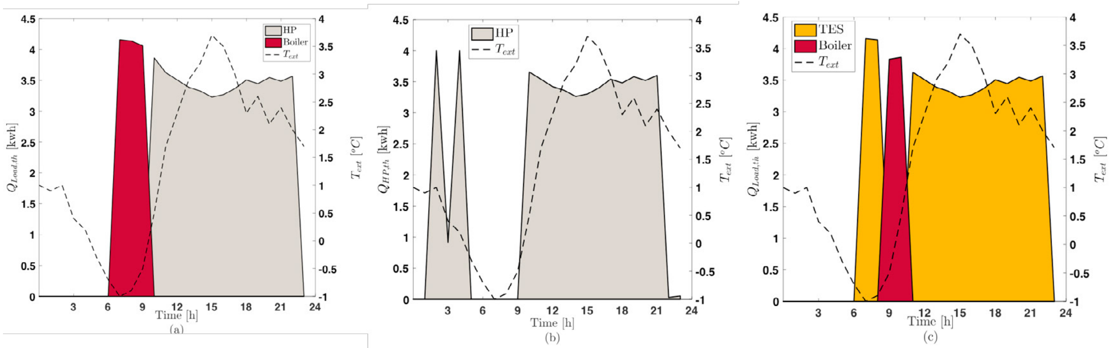

Fig. 3. Reference case - Optimal control strategy: (a) with no TES, (b),(c) with TES.

It can be noted how the TES makes the system more flexible and able to take advantage from the most profitable working conditions of the heat pump. In the configuration without TES, the boiler is used to meet the load during all those hours in which the external temperature is below the minimum value required by the heat pump to be operated. On the other hand, in the configuration with the TES, the heat pump can operate to charge the storage in the early hours of the day, when no load demand occurs. By this way, a reduction of the load share covered by the boiler occurs, with a consequent reduction of the system operative cost. In order to assess the impact of DR actions on the reference optimal control strategies, Fig. 4 shows how the thermal power delivered by the heat pump is affected by a 50% reduction (α = 0.5) in its electrical energy consumption due to the DR for both configuration considered: without TES and with 0.5 m^3 water storage tank, respectively. Regarding the configuration without TES, it can be noted that

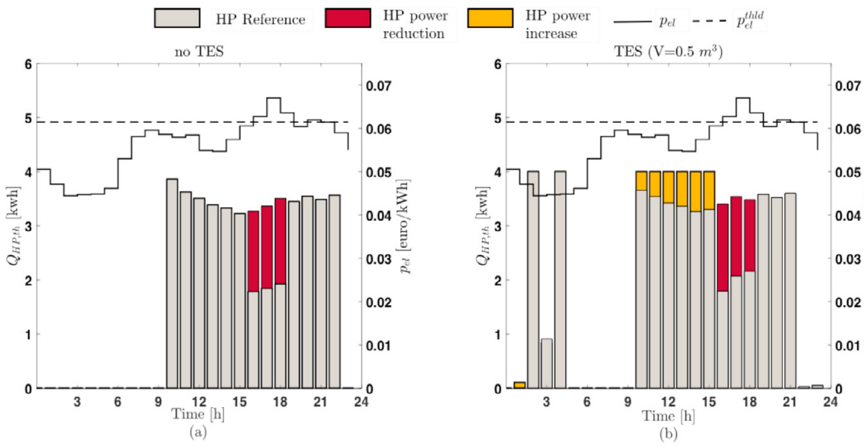

Fig. 4. Optimal operation of the heat pump under a DR program with α = 0.5 (a) system with no TES; (b) system with TES.

no variations of the heat pump operations occur during the hours of the day in which no active DR actions are in place. As a consequence, an increase in the use of the gas boiler during the hours in which the DR action is active (between 4 and 6 pm) is observed (see Fig. 5). On the other hand, a different behaviour can be observed when a TES is considered: the controller increases the use of the heat pump before the hours of the day in which the DR is active, with the aim of minimising the use of the gas boiler and, consequently, the total cost. Finally, Fig. 6 shows the results related to different DR actions, considered by varying the value of the parameter α within the range 0.3-1, and two different TES capacities. It can be noted that for both TES sizes the load-share covered by the gas boiler is lower compared to the case without TES, with consequent lower operational costs. Nevertheless, it must be considered that this load-shifting from the boiler to the heat pump can lead to a cost-saving only if the heat pump operates with a COP higher than a threshold value, based on the electricity and natural gas tariffs as well as on the gas boiler efficiency: $COP^{thld} = p_{el} \cdot \left(\eta_B / p_{gas}\right)$.

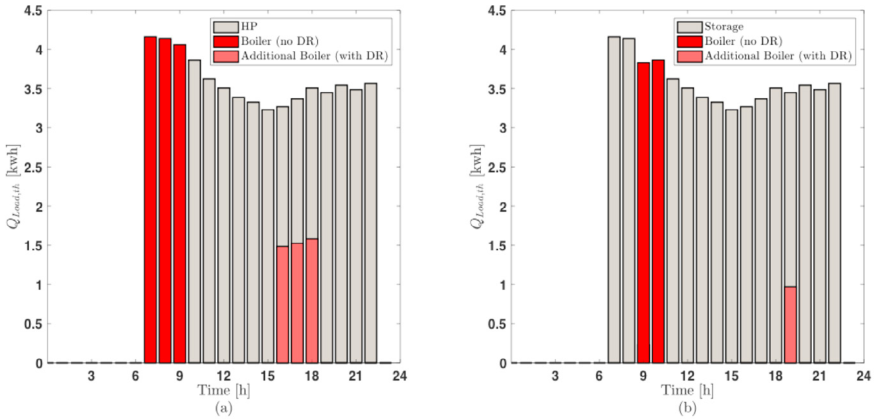

Fig. 5. Load sharing between the generators in the reference case (no DR) and under a DR program with $\alpha = 0.5$ (a) system with no TES; (b) system with TES.

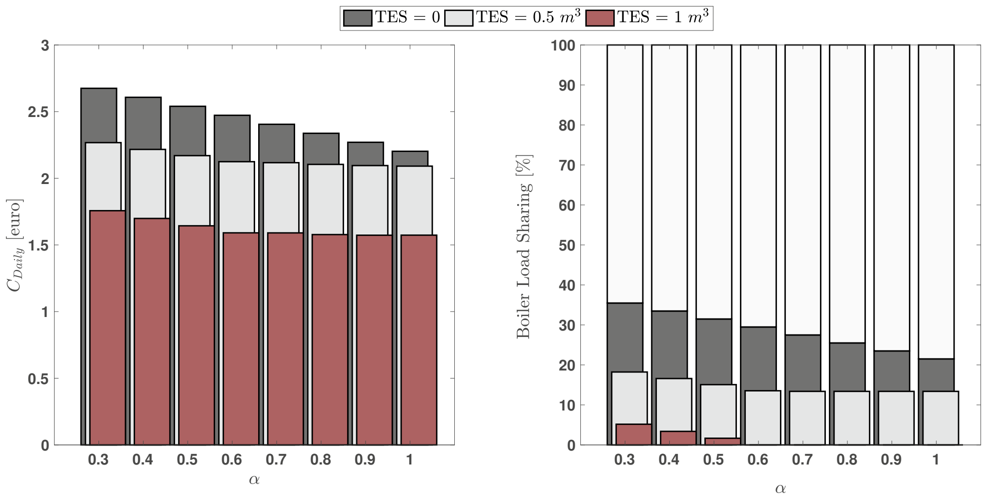

Fig. 6. Effects of different Demand Response program (α) on: (a) Daily Cost for flexibility; (b) Boiler Load Sharing.

7. Conclusions

The present paper investigated the flexibility potential associated with a residential building equipped with an optimally controlled hybrid generator (electrically-driven air-source heat pump and a gas boiler) coupled with a thermal storage tank under different demand response strategies. Results showed a reduction of the energy cost up to 35% when a storage capacity is coupled with the hybrid generator, leading to a more efficient operation of the whole system. In fact, thanks to the flexibility offered by the storage tank, the controller is able to operate the heat pump by taking advantage of its most profitable working conditions. Moreover, the capacity of the heat pump to shift in time the thermal load appears to be connected with the available storage capacity. Halving the storage capacity, from 1 m^3 to 0.5 m^3, the maximum achievable cost-saving decreases from 35% to 15%, but at the same time the investment cost required for the TES, which can be estimated at around 10 €/kWh [17], decrease. As the achievable flexibility has been shown to be strictly dependent on the storage capacity and operations, which in turn are affected by the generators sizing, further work will address the effects of those parameters. Moreover, the present work focused only on the generation-side level, neglecting all those measures that can be implemented on the building-level to provide additional flexibility (e.g., by varying the internal temperature set-point and exploiting the thermal inertia of the building). At this end, a model able to describe the building dynamics have also to be considered. The impact of the generators efficiencies on the costs for flexibility will be further investigated too.

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