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Experimental Validation of a Tool for the Economic Operation Optimization of a Hybrid Energy System

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ABSTRACT

Hybrid energy systems (HESs) can bring together different types of generation, storage, and consumption units in a single system, improving the overall performance compared to a system that depends on a single source, thanks to the exploitation of synergies coming for interplay of multiple energy carriers. To achieve these benefits, daily operation is crucial and can represent a challenging task due to the coupling of energy technologies and processes, the time-varying user demands and the need to reach optimal economic performance. The contribution of this paper is to present the experimental validation of a tool for the economic operation optimization of a HES, by using as case study one of the experimental plants available at ENEA Portici Research Centre. The HES consists of a combined heat and power (CHP) system, an auxiliary gas-fired boiler and a thermal energy storage for satisfying the electrical and thermal demand of a single-family house. The experimental simulations of the CHP implementing the optimized daily scheduling and a conventional ON/OFF logic are carried out to compare results and demonstrate the effectiveness of the proposed optimization tool for minimizing the net daily energy costs of the HES.

1. INTRODUCTION

Hybrid energy systems (HESs) can bring together different types of generation, storage, and consumption units in a single system, improving the overall performance compared to a system that depends on a single source, thanks to the exploitation of synergies coming for interplay of multiple energy carriers [1-3]. Moreover, they represent a promising solution for standalone applications for the satisfaction of end-user's multi-energy demand including electricity, heating, and cooling [4-6]. To achieve these benefits, daily operation is crucial and can represent a challenging task due to the coupling of energy technologies and processes, the time-varying user demands and the need to reach optimal economic performances [7-9].

In the literature, several studies have been conducted for the operation optimization of HESs, by considering economic factors and also both economic and environmental factors through a multi-objective approach [10-13]. However, most tools available in the literature have been tested through numerical case studies [14-19], thereby highlighting a gap in the experimental implementation and/or validation of these tools in real-world contexts, including lab-scale applications.

The aim of this paper is to present the experimental validation of a tool for the economic operation optimization of a HES, by using as case study one of the experimental plants available at ENEA Portici Research Centre. The HES consists of a combined heat and power (CHP) system, an auxiliary gas-fired boiler and a thermal energy storage for satisfying the electrical and thermal demand of a single-family house. The optimization tool is based on a mixed-integer linear programming (MILP) approach and aims to determine the optimal daily scheduling of the technologies in the HES and the amount of electricity taken and fed from/into the grid. The optimization of the operating schedule is on a daily basis and is conducted on several consecutive days, characterized by the same input data, in order to find a periodic solution to be validated experimentally. Therefore, the economic objective function is formulated as the sum of the daily objective functions, i.e., the net daily energy cost to minimize. The latter consists of the sum of the costs for the purchase of electricity from the grid and natural gas minus the revenue for the sale of electricity fed back into the grid. The experimental simulation of the CHP implementing the optimized daily schedule and a conventional ON/OFF logic are carried out to compare results and demonstrate the effectiveness of the proposed optimization tool in minimizing the net daily energy costs for the HES. Results highlight that the CHP works for more hours in the optimized case, with a consequent larger amount of electricity fed back to the grid as compared to the conventional ON/OFF logic. The latter, combined with the fact that with the optimized schedule the electricity production of the CHP is concentrated in the hours with the highest amount of electricity fed into the grid, entails an economic balance in favor of the optimized schedule, thereby demonstrating the effectiveness of the optimization tool.

In the following, the operation optimization model is described in Section 2, whereas the characteristics of the user and of the simulated CHP system are described in Section 3. The description of the experimental plant along with the experimental text conducted in the study are presented in Section 4. The results obtained with the optimized scheduling and by implementing a conventional ON/OFF logic are discussed in Section 5, by also presenting a comparison in terms of energy consumption and economic performance for the HES under study.

2. OPERATION OPTIMIZATION MODEL FOR THE EXPERIMENTAL HES

Figure 1 shows the scheme of the HES under study used for the establishment of the operation optimization model with reference to the experimental case. In the scheme, the CHP and electrical grid are used to satisfy the user's electrical load, considering that the electricity supplied by the CHP can be both used for self-consumption and fed into the grid. To satisfy the thermal load of domestic hot water (DHW) and space heating (SH), the CHP, the auxiliary gas boiler and the thermal storage can be used.

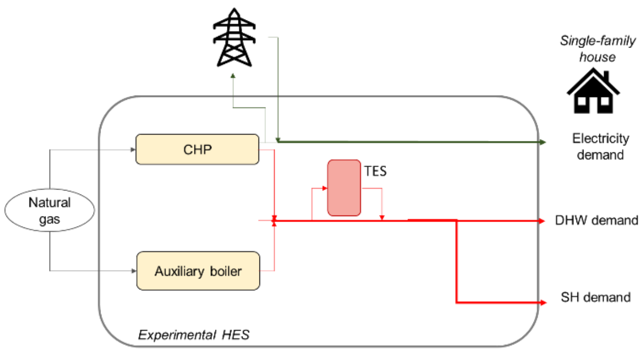

Figure 1. Scheme of the experimental HES for the operation optimization model

The operation optimization tool has a time horizon of 1 day with 1 hour as time step and is based on a MILP approach, taking into consideration the real constraints of the experimental HES. The aim of the tool is to determine the optimal scheduling of the HES that allows minimizing total net daily energy costs.

The input data to the optimization tool are the electrical and thermal loads of the user, the characteristics of the energy technologies, the prices of input energy carriers and the day-ahead market price, while the output is represented by the hourly schedule of operation of the HES optimized from an economic point of view, and by the various terms that compose the thermal and electric energy balance, and the economic balance relating to the optimized hourly schedule.

2.1 Decision variables

The decision variables of the optimization problem include both binary and continuous decision variables and are listed below:

- On/off status of technologies.
- Power and heating rate provided by technologies.
- Charging/discharging heat rate to/from thermal storage.
- Electricity purchased from the grid.
- Electricity fed into the grid.

The on/off states of technologies represent binary decision variables, while all the other listed decision variables are continuous.

2.2 Objective function

The economic objective function is formulated as the total daily net energy cost to be minimized, taking into account costs incurred for the purchase of electricity from the grid and natural gas to power the CHP and the boiler, and the revenues obtained from the sale of the electricity produced by the CHP. This objective function is formulated as:

$$\text{Net daily cost} = \sum_{t} \left(E_t^{Buy} \Pi_t^{Grid} + G_{i,t}^{Buy} \Pi^{Gas} - E_{CHP,t}^{Sell} \Pi_t^{DA} \right) Dt, \quad i \in \{CHP, Boil\} \tag{1}$$

In Eq. (1), E_t^{Buy} is the share of electricity purchased by the grid at time *t* and at the price Π_t^{Grid}; $G_{i,t}^{Buy}$ is the total quantity of natural gas purchased at time *t* and at the price Π^{Gas}; $E_{CHP,t}^{Sell}$ represents the share of electricity produced by the CHP fed into the grid at time *t* and at the day-ahead market price Π_t^{DA}; and *Dt* is the hourly time-step.

The optimization of the operating schedule is on a daily basis and has been conducted on several consecutive days, characterized by the same input data, in order to find a periodic solution to be validated experimentally. Therefore, the economic objective function considered for the experimental validation has been formulated as the sum of the daily objective functions.

2.3 Model constraints

The constraints of the optimization model consist of:

- Operating constraints of the technologies in the HES.
- Energy balance constraints for satisfying the hourly electrical and thermal loads of the user.

With reference to the operating constraints of the technologies, in order to maintain the linearity of the optimization model, the hypothesis of constant efficiency has been made, therefore assuming that it does not vary with the load.

The common constraint for all technologies is the capacity constraint, formulated below for the CHP:

$$E_{CHP}^{min} \times_{CHP,t} \leq E_{CHP,t} \leq E_{CHP}^{max} \times_{CHP,t}, \forall t \tag{2}$$

The electrical power delivered is therefore limited by the minimum load and the maximum power, if the technology is in use, namely if the binary decision variable, $x_{CHP,t}$ is equal to 1. For the CHP, the ramp rate constraint is also established, limiting the variation of the total electrical power delivered between two subsequent time-steps, within the respective Ramp-Down and Ramp-Up. The total electrical power supplied by the CHP is equal to the sum of the electrical power used for self-consumption and that fed into the grid:

$$E_{CHP,t} = E_{CHP,t}^{Self} + E_{CHP,t}^{Sell}, \forall t \tag{3}$$

The quantity of natural gas needed by the CHP is formulated as:

$$G^{Buy}_{CHP,t} = E_{CHP,t}/(\eta_{CHP,e}LHV_{gas}), \forall t \tag{4}$$

whereas the recovered heat rate is formulated as:

$$H_{CHP,t} = E_{CHP,t}\eta_{CHP,th}/\eta_{CHP,e}, \forall t \tag{5}$$

As for the auxiliary boiler, the quantity of gas consumed is formulated similar to Eq. (4), by considering the conversion efficiency of the boiler.

As for the thermal storage system, the state dynamic is formulated as:

$$H_{TES,t} = H_{TES,t-1}\big(1 - \varphi_{TES}(Dt)\big) + (H^{Ch}_{TES,t} - H^{Disch}_{TES,t})Dt, \forall t \tag{6}$$

Energy balance constraints are necessary to ensure that assigned user's loads are met. With reference to the electricity energy balance, the electricity load must be satisfied by the electricity supplied by the CHP and the electricity from the electrical grid:

$$E^{Dem}_{t} = E^{Self}_{CHP,t} + E^{Buy}_{t}, \forall t \tag{7}$$

With reference to the thermal energy balance for DHW, the load must be satisfied by the CHP, the boiler and the storage, i.e.:

$$H^{DHW}_{t} = H^{DHW}_{CHP,t} + H^{DHW}_{Boil,t} + H^{DHW,Disch}_{TES,t} - H^{DHW,Ch}_{TES,t}, \forall t \tag{8}$$

The thermal energy balance for SH demand can be formulated similarly.

The optimization problem is linear and includes both binary and continuous variables and is solved using the branch-and-cut algorithm, which is particularly efficient for MILP-type models.

3. CHARACTERISTICS OF THE USER AND THE SIMULATED CHP SYSTEM

The user considered for the experimental validation of the tool presented in the previous section has been selected such that to experimentally simulate the real thermal loads. Therefore, a single-family house has been considered, characterized by a useful surface area of 200m^2, a shape factor of 0.9m^{-1}, and located in the Italian E climatic zone.

The hourly profiles of the thermal and electrical loads used for the simulations are related to a typical day in the month of March and have been calculated using the approach presented by Mongibello et al. [20]. In details, the hourly load profiles have been obtained considering an annual thermal demand for SH equal to 68 kWh/m^2/year, an annual thermal demand for DHW of 15 kWh/m^2/year, and an annual electrical demand, relating to domestic electricity consumption excluding that for air conditioning in summer, equal to 18kWh/m^2/year.

Table 1. Characteristics of the simulated technologies

Technology	Size	Efficiency	
		Electric	Thermal
CHP	5.4kW$_{th}$; 2.275kW$_{el}$	0.286	0.679
Auxiliary boiler	5.4kW		0.80
TES	9.5kWh		

The simulated CHP system consists of an internal combustion engine as prime mover fueled by natural gas, an auxiliary boiler also fueled by natural gas, and a thermal storage system as represented in Figure 1. Table 1 shows the technical characteristics of these technologies.

As regards the economic data, the price of natural gas has been set equal to 0.85€/Nm^3, or 0.77€/Nm^3 if consumed by the CHP system due to the discount on the excise duty, and the price of purchasing electricity from the grid has been set equal to 0.17€/kWh. The economic value of the electricity produced and fed into the grid has been considered varying with time according to the Italian day-ahead market prices.

4. DESCRIPTION OF THE EXPERIMENTAL PLANT AND TESTS

Figure 2 shows a photo of the system used for the experimental implementation of the optimized schedule resulting from the optimization tool and of a conventional ON/OFF strategy, both applied to the experimental case study previously described.

The thermal storage system consists of a commercial cylindrical thermally insulated tank 1.27m high, with an internal diameter of 0.65m, and a total capacity of approximately 420 liters, including the volume occupied by the two 1" coil heat exchangers with which it is equipped, each with a heat exchange area of approximately 2m^2. The lower coil of the storage tank is connected to the thermal circuit of the heat generator, while the upper coil is connected to the user circuit, i.e., the circuit in which there is a heat exchanger that allows simulating the user thermal loads for SH. For both circuits, water is used as heat transfer fluid.

Figures 3 and 4 show the layout of the heat generator circuit and that of the user, respectively. Regarding the heat generator circuit, the main component is represented by the electric heater, capable of transferring up to 24kW @ 420V (15kW @ 380V) of thermal power to the heat transfer fluid. As regards the user circuit, the main component is represented by the finned tube air-water heat exchanger, capable of dissipating up to 15kW of thermal power. As regards the simulation of the thermal load relative to the DHW, this is carried out by varying the discharge flow rate of the thermal storage tank via the VM1 modulating valve. The flow rates of the heat transfer fluid in the two circuits and that of the tank discharge are measured using differential pressure sensors with an accuracy equal to ± 5% of the measured value, while all temperatures are measured with type T class 1 thermocouples, with an accuracy equal to ±0.5°C.

Figure 2. Experimental system used for the implementation of the optimization tool

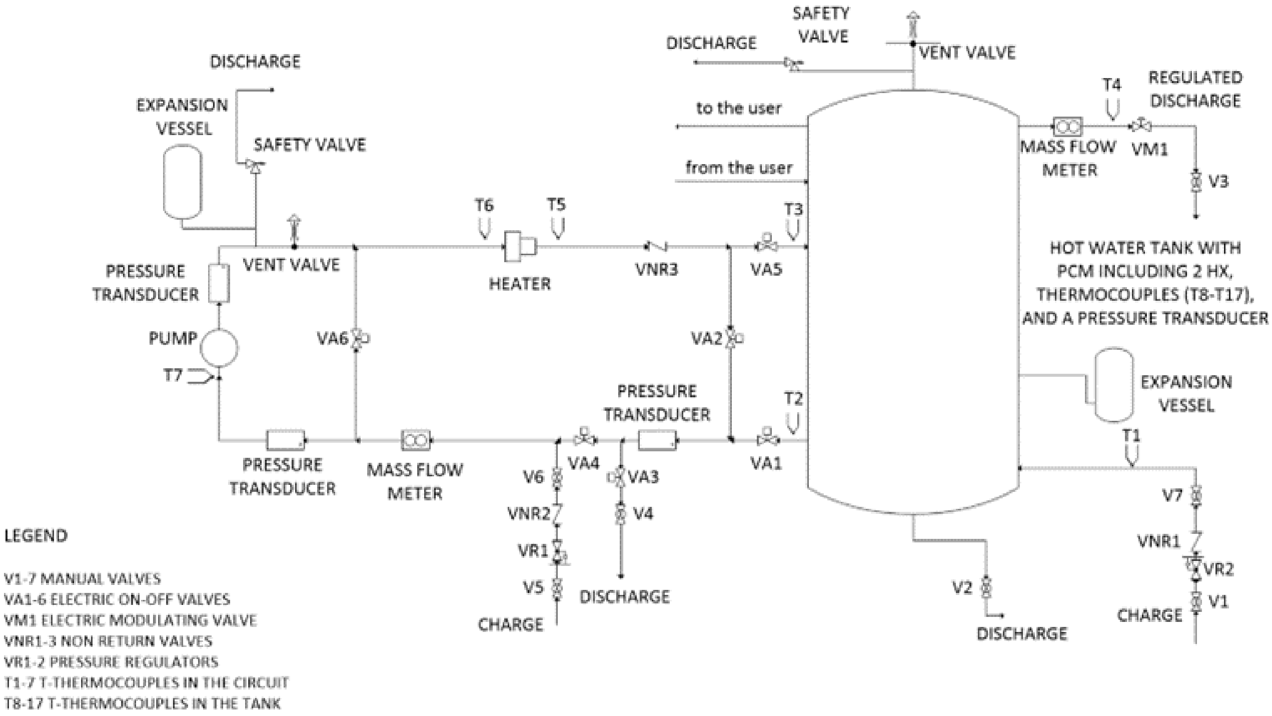

Figure 3. Scheme of the heat generator circuit

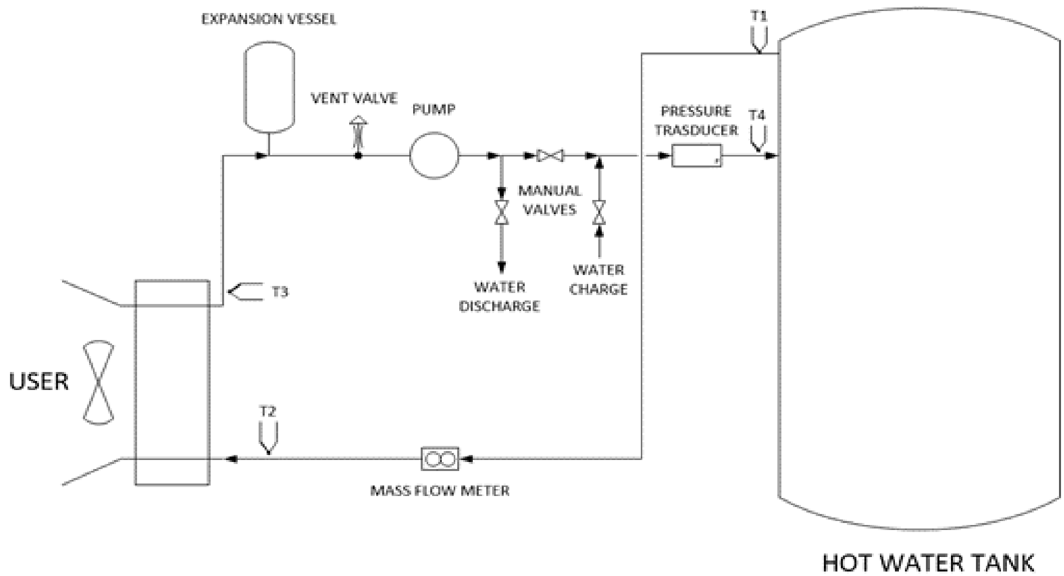

Figure 4. Scheme of the user circuit

As concerns the prime mover, in both the experimental tests carried out, the ON/OFF operation at full load is implemented, without the possibility of partial load, on an hourly basis. The thermal production of the prime mover and the thermal loads were simulated experimentally, while the thermal production of the auxiliary boiler, the electrical production of the prime mover, and the electrical loads were simulated on the computer using the data reported in previous section.

5. RESULTS

5.1 Results obtained with the optimized scheduling

The hourly schedule resulting from the application of the optimization tool to the case study of the single-family house prescribes that the CHP, in the simulated standard day, must operate from hour 8 to 12, at hour 15, and from hour 17 to 22. In the remaining hours, the CHP must be turned off. This schedule was applied to the experimental system using the following water flow rates: the flow rate of the heat transfer fluid in the generator circuit is equal to 0.4kg/s; the flow rate of the heat transfer fluid in the user circuit is equal to 0.15kg/s.

As regards the discharge flow rate of DHW from the storage tank, this can vary linearly between 0.1 and 0.2kg/s, depending on the discharge temperature. During the hours in which the CHP is scheduled to operate, the electric heater is turned off if the temperature at its outlet exceeds 95°C, or if the maximum temperature in the storage tank exceeds 85°C. If one of the aforementioned conditions occurs, the electric heater is subsequently reactivated when the average temperature inside the tank drops below 80°C, provided that at the moment in which this occurs, the optimized schedule prescribes that the CHP is running, otherwise the electric heater remains off.

The same schedule and the same loads were simulated for several consecutive days in order to obtain experimental results that are repeated as they are day after day. This condition was reached on the second day of simulation, the results of which are reported below.

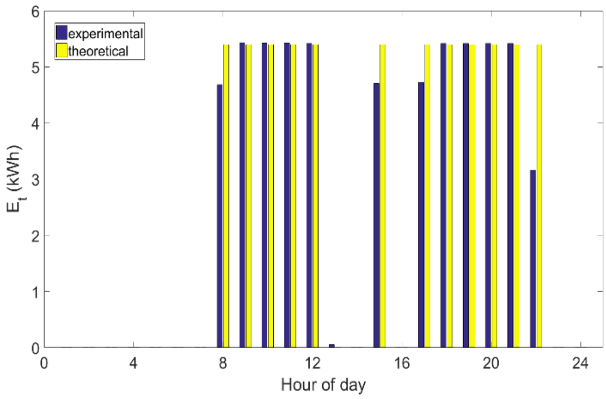

Figure 5. Comparison between the thermal energy produced by the electric heater and that resulting from the optimization tool

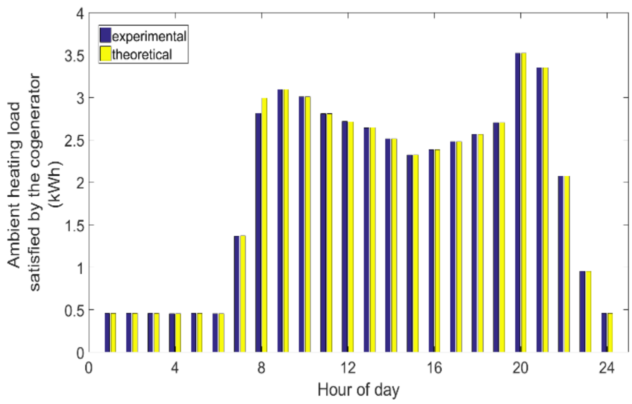

Figure 6. Comparison between the experimental and theoretical SH load satisfied by the CHP

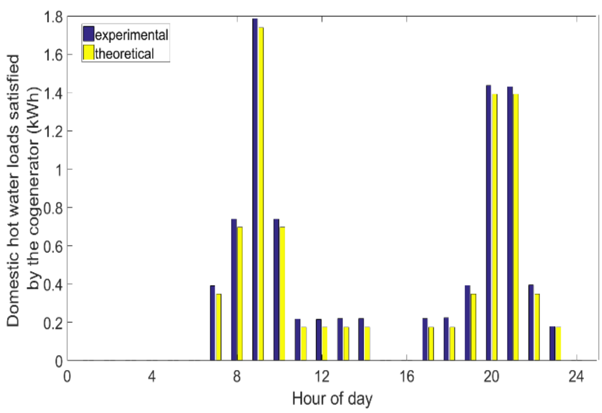

Figure 7. Comparison between the experimental and theoretical DHW consumption satisfied by the CHP

Figure 5 shows a comparison between the thermal energy transferred from the electric heater to the heat transfer fluid, and that generated by the CHP resulting from the optimization tool. It can be seen that in the hours 8, 15, 17, and 24, the experimental thermal production does not correspond to that of the optimization tool. This result is due to the fact that, at the beginning of the 8, 15, and 17 hours, i.e., at the transition from the OFF state to the ON state of the heater, the latter takes some time to bring the outlet temperature to the value of set-point corresponding to the theoretical power, and to the fact that, during the 24th hour, the maximum temperature in the tank reaches the maximum allowable value (85°C), i.e., the storage tank reaches its maximum capacity, for which the heater electric is deactivated.

Figure 6 shows a comparison between the experimental data and those resulting from the implementation of the optimization tool relative to the thermal load for SH satisfied by the CHP, while Figure 7 shows the one relative to DHW consumption satisfied by the CHP.

In both the figures, the data resulting from the implementation of the optimization tool coincide with the assigned theoretical loads. This implies that the gas consumption of the auxiliary boiler resulting from the optimization tool is equal to zero at all hours of the day. This does not occur in the experimental simulation. In fact, concerning thermal load for SH, the experimental results indicate that, in hour 8, the thermal energy produced by the CHP together with the stored one are not sufficient to satisfy the load, so an integration by the auxiliary boiler is necessary.

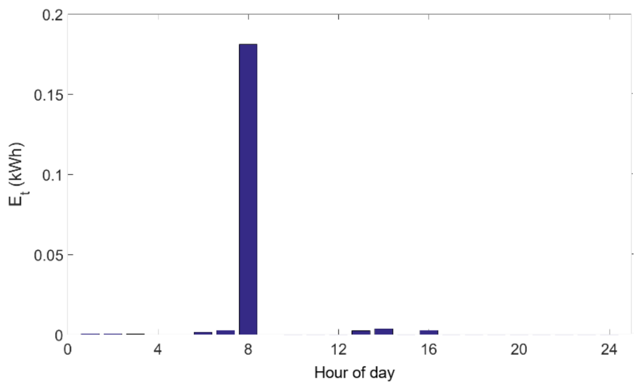

Figure 8. Thermal load satisfied by the auxiliary boiler in the experimental case

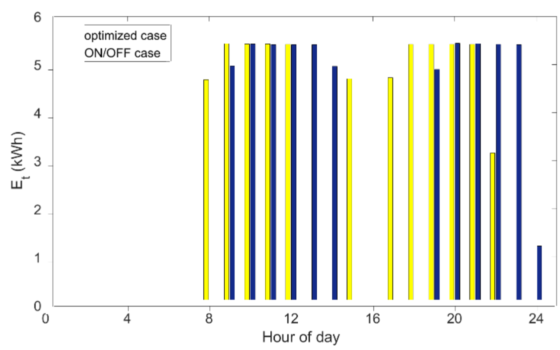

Figure 9. Comparison between the thermal energy produced by the electric heater with ON/OFF and that resulting from the optimization tool

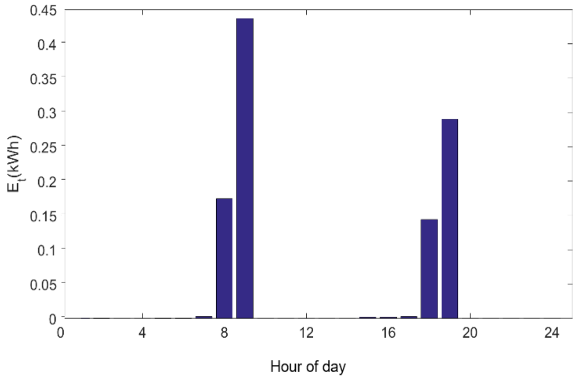

Figure 10. Thermal load satisfied by the auxiliary boiler

Figure 8 shows an estimate of the energy produced by the auxiliary boiler during the day whole relative to the experimental case, calculated, in each hour, as the difference between the theoretical thermal load and that satisfied by the CHP.

5.2 Results obtained by implementing a conventional ON/OFF logic

The conventional ON/OFF logic prescribes that the CHP, i.e., the electric heater that simulates its thermal production, is normally in the ON state during the standard day, and that it is turned off if the temperature at the outlet of the electric heater exceeds 95°C, or if the maximum temperature in the storage tank exceeds 85°C. If one of the aforementioned conditions occurs, the electric heater is subsequently reactivated when the average temperature inside the tank drops below 55°C. This logic was applied to the experimental plant using the same configuration of the uncontrolled experimental parameters used for the implementation of the optimized schedule, and also in this case the periodicity of the CHP operation was reached on the second day of simulation, which results are reported below.

Figure 9 shows the thermal energy produced by the electric heater in the experimental case with conventional ON/OFF operation and in the one with optimized schedule.

It can be seen that the production of the CHP in the optimized case is concentrated more in the hours in which the economic value of the electricity fed into the grid is higher. Furthermore, the total production of the CHP in the conventional case is lower compared to the optimized case, implying a higher use of the boiler in this case, as can be seen in Figure 10 showing an estimate of the energy produced by the auxiliary boiler during the day.

5.3 Comparison between the results obtained in the two experimentally simulated cases

In this section, the results obtained with the optimized scheduling of the HES and by implementing a conventional ON/OFF logic are compared. Table 2 reports the gas consumption and electricity withdrawn and injected into the grid, while Table 3 reports the costs and revenues resulting from the two experimental simulations carried out with the optimized scheduling and implementing a conventional ON/OFF logic.

Table 2. Gas and electricity consumption, and electricity fed into the grid for one day

	CHP Gas Consumption (Nm^3)	**Boiler Gas Consumption (Nm^3)**	**Electricity from the Grid (kWh)**	**Electricity to the Grid (kWh)**
Optimized schedule	9.24	0.02	4.11	15.67
ON/OFF logic	9.05	0.14	3.92	15.14

Table 3. Costs and revenues for one day

	Cost for CHP (€)	**Cost for Boiler (€)**	**Cost Electricity from the Grid (€)**	**Revenue for Selling Electricity (€)**
Optimized schedule	7.11	0.02	0.70	1.32
ON/OFF logic	6.97	0.12	0.67	1.24

The results in Table 3 highlight that the CHP consumes more and therefore works for more hours in the optimized case, with a consequent larger amount of electricity fed back into the grid compared to the conventional ON/OFF logic. The latter, combined with the fact that with the optimized schedule the electricity production of the CHP is concentrated in the hours with the highest amount of electricity fed into the grid, entails an economic balance in favor of the optimized schedule, thereby demonstrating the effectiveness of the optimization tool, as can be seen from the economic data reported in Table 3.

6. CONCLUSIONS

This work presents the experimental validation of a model for the economic operation optimization of a hybrid energy system (HES), by using one of the experimental plants available at ENEA Portici Research Centre. The HES consists of a combined heat and power (CHP) system, an auxiliary gas-fired boiler and a thermal energy storage for satisfying the electrical and thermal demand of a single-family house. The optimization model is based on a mixed-integer linear programming approach and aims to determine the optimal daily scheduling of the technologies in the HES and the amount of electricity taken and fed from/into the grid. The optimization of the operating schedule is on a daily basis and is conducted on several consecutive days, characterized by the same input data, in order to find a periodic solution to be validated experimentally. Therefore, the economic objective function is formulated as the sum of the daily objective functions, i.e., the net daily energy cost to minimize. The latter consists of the sum of the costs for the purchase of electricity and natural gas minus the revenue for the sale of electricity fed back to the grid. For the case study, results obtained implementing experimentally the optimized daily schedule and a conventional ON/OFF logic are presented and compared to demonstrate the effectiveness of the proposed optimization tool. In detail, it is found that the CHP works for more hours in the optimized case, with a consequent larger amount of electricity fed into the grid as compared to the conventional ON/OFF logic. The latter, combined with the fact that with the optimized schedule the electricity production of the CHP is concentrated in the hours with the highest amount of electricity fed into the grid, entails an economic balance in favor of the optimized schedule, thereby demonstrating the effectiveness of the proposed tool in optimizing the economic performance of the HES at lab-scale.

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NOMENCLATURE

D_t	Time step (h)
E_t	Electrical power (kW)
G_t	Volumetric flow rate of natural gas (Nm^3/h)
H_t	Heat rate (kW)
LHV_{gas}	Lower heat value of natural gas (kWh/Nm^3)
x_t	Binary decision variable

Greek symbols

φ_{TES}	Thermal loss fraction of TES
η	Conversion efficiency
Π	Price of the energy carrier (€/kWh)-(€/Nm^3)

Superscripts/Subscripts

Ch	Charging
DA	Day-ahead market
Disch	Discharging
i	Technology index
max	Maximum
min	Minimum