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Optimal Operations Management of Hybrid Energy Systems Through Short-Term Atmospheric and Demand Forecasts

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Abstract

The complexity of systems for energy production through renewable energy sources (RESs) is constantly increasing considering the integration of multiple modules, e.g. different RES sources, energy storage in batteries and connection to national grid for energy trade purpose. This significant complexity could represent a threat but also an opportunity if adequately managed. Aim of this paper is to propose two different approaches to manage the hourly electricity flows between the different components of a hybrid energy system (HES) fueled by PV modules and a wind turbine, equipped with a battery storage system (BES) to satisfy the demand of a user load with the opportunity to sell and purchase the electricity to/from the national grid. The first approach is a heuristic algorithm (HA) which defines robust but constant dispatching criteria of the energy flows between the HES components considering just the current value of energy production and demand with the aim of minimizing the electricity purchased by the grid. On the contrary, the second approach is a mixed integer linear programing (MILP) model which defines the optimal value of the energy flows to maximize the net profit of the HES operations determined by the electricity sales revenues minus the energy purchase costs. The developed MILP leverages the short-term forecast of the atmospheric conditions and user demand as well it considers variable energy sale and purchase pricing in the different daily hours. Both these approaches have been tested and validated through a case study of a residential building in which multiple households live located in the suburban area of Munich (Germany). The obtained results highlight how the MILP outperforms HA considering the net profit achievable weekly due to electricity trade with the grid. In particular, the MILP improve the HA economic performance of the HES operation management of 18% on average over the different months of the year.

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Keywords: Energy flows; operations management; short-term forecast; renewable energy; battery storage system; optmization model.

1. Introduction and literature review

During the latest decades, several literature contributions focused in the development of mathematical model for renewable energy sources (RES) plant optimal design, defining the best size of each component to purchase and install in the plant [1,2]. These approaches are targeted to the initial investment optimization since it represents the greatest portion of the expenditures which occur during the RES plants entire lifetime [3-5]. During the latest years such methods had to consider a further component which more and more often is installed in RES plants, e.g. battery energy storage systems (BESs) [6]. Aim of these researches is the definition of the optimal size of each RES plant module considering the specific value and profile of atmospheric conditions (wind, irradiance, temperature, etc.), user load demand as well as electricity sale and purchase price for the considered case study [7]. However, no consideration is typically provided once the RES plant is installed and ready to produce electricity. Indeed, these traditional approaches usually manage the energy flows between the energy system component guaranteeing a feasible functional pattern but with limited focus on the best management strategy. These approaches miss the terrific opportunity to efficiently manage the operation phase of such RES plant which could result in superior techno-economic performances [8]. A proper management of the BES charging and discharging cycles could prolong the lifetime of this expensive component. The exploitation of the different electricity sale and purchase prices of the different time slot could significantly improve the operating revenues. The consideration of the atmospheric condition pattern as well as the one of the energy demand profile could minimize the quantity of energy purchased by fossil sources [9-11]. All these opportunities have been embraced by a bunch of researchers which developed different strategies, numerical methods and mathematical models aimed at the optimal management of energy plants fueled by multiple RES equipped with BES [12].

[13] propose an optimization model to define the hourly energy flows between the different components of a RES plant equipped with photovoltaic (PV) modules, a BES and connected to the national grid to sell and purchase the electricity. Furthermore, this contribution considers the different values of the electricity selling and purchasing prices during the day. To maximize the benefit of variable electricity pricing and to mitigate the fluctuation and uncertainty of PV energy production, the authors force the user load to a certain flexibility in its electricity demand. This strong limitation to the practical adoption of these category of energy management strategies is overcame by [14]. These authors propose a set of artificial neural network to forecast the user demand without any imposition or modification to its needs and habits. This method is adopted to evaluate the trends and patterns of the electricity demand and offer this result as input to a meta-heuristic model which dispatch the hourly energy flows between the RES plant components. [15] provide a further development of this approach extending the forecasting method to the energy produced by the RES. Indeed, an accurate evaluation of the available energy in the different portions of the day is of major importance to maximize the system efficiency. This latter evolution of energy management strategy has been adopted by several other researchers to optimize the operation of energy system fueled by RESs. A relevant upgrade of such models is proposed by [16] to solve a practical problem faced. Certain installation sites are distinguished both by remarkable values of irradiance and also wind speed. These circumstances make them the ideal scenario to for hybrid energy system (HES) for electricity production. Such evolution to HES has a terrific impact on the management of the energy flows, in particular for HES equipped with BES. The strategy for energy management for such systems represent a crucial aspect of their operating phase, since it heavily effects the efficiency and efficacy of the entire HES. [17] propose and validate three different heuristic algorithms to manage the hourly energy flows of such HES equipped with a BES and connected to the national grid for electricity trade purpose at constant price. The author implemented all these algorithms in a real case study to assess their performances measure in terms of net cash flow determined by the sale/purchase processes and the total amount of energy purchased by the grid (e.g. produced by fossil fuels) to satisfy the user load every hour of operation. The obtained results are promising and suggest to further investigate in such direction, eventually developing customized optimization models, since the three algorithms differs of about 8% for the economic aspect and 13% for the environmental one.

Considering the presented literature framework this manuscript aims to include the multiple and peculiar aspects which distinguish the management of the energy flows between the different components of a HES fueled by multiple

RESs equipped with a BES and connected to the national grid to sell and purchase electricity at variable price. This complex problem is tackled by an original heuristic algorithm which adequately and simultaneously tackle the multiple aspects of such systems devoted to energy production. The proposed algorithm considers a HES with components of defined size and it aims to dispatch the hourly energy flows between the different plant modules to constantly minimize the energy purchased by the grid and the energy dissipated through the DC/AC electricity conversion processes between the different HES modules considering the user load as an immutable constraint to constantly satisfy. Furthermore, to guarantee superior performances to the HES, a mixed integer linear programming (MILP) optimization model is proposed to define the hourly energy flows between the system components and maximize the net cash flow determined by the electricity trade with the grid. The model is fed using as input data the short-term (e.g. 48 hours) forecast of the atmospheric conditions and load energy demand. A particular attention is determined by the management of the charging and discharging cycles of the BES which are of fundamental importance to minimize the electricity purchased by the grid, thus maximizing the HES operating economic performance.

This manuscript is organized as it follows. Section 2 presents the HES architecture defining the different modules as well as their integration focusing on the different type of electricity flows between them, the load and the national grid. Section 3 proposes the original heuristic algorithm developed to manage the operations of such energy production plant considering the size of the HES modules as given and fixed. Section 4 analyses the mixed integer linear programming model targeted at the energy flows optimization leveraging short term atmospheric and demand forecast to maximize the system economic performances. Section 5 describes the real case study adopted to test and validate both the heuristic algorithm and the optimization model presenting the input data, i.e. their average values as well as their daily trend. The obtained results are extensively discussed in Section 6 before drawing the paper conclusions together with suggestions for further research in the last Section 7.

Nomenclature

PV	photovoltaic system
P_0	nominal power of the photov. system [kW]
W	wind turbine
P_W	nominal power of the wind turbine [kW]
B	battery energy storage system (BES)
K_{max}	battery nominal capacity [kWh]
L	user electricity load
G	electricity national grid
h	hour index
$E_{L,h}$	energy demand of the user load at h [kWh]
$E_{PV,h}$	energy supplied by PV system at h [kWh]
$E_{W,h}$	energy supplied by wind turbine at h [kWh]
$E_{PVL,h}$	energy flow from PV to L at hour h [kWh]
$E_{PVB,h}$	energy flow from PV to B at hour h [kWh]
$E_{PVG,h}$	energy flow from PV to G at hour h [kWh]
$E_{WL,h}$	energy flow from W to L at hour h [kWh]
$E_{WB,h}$	energy flow from W to B at hour h [kWh]
$E_{WG,h}$	energy flow from W to G at hour h [kWh]
$E_{BL,h}$	energy flow from B to L at hour h [kWh]
$E_{GL,h}$	energy flow from G to L at hour h [kWh]
SOC_h	state of charge of BES system at h [kWh]
η_{ch}	BES system charging efficiency [ ]
η_{dch}	BES system discharging efficiency [ ]
σ	BES system hourly self-discharge rate [ ]
η_{inv}	Inverter, DC/AC, efficiency [ ]
η_{conv}	Converter, AC/DC, efficiency [ ]

HI_h	direct solar radiation $\left[\frac{kW\,h}{m^2}\right]$
HR	max. value of direct solar radiation $\left[\frac{kW\,h}{m^2}\right]$
$\eta_{pv,h}$	PV system overall efficiency [ ]
$T_{c,h}$	PV cell temperature for hour h [°C]
η_{mod}	PV module conversion efficiency [ ]
η_{pc}	PV system power conditioning efficien. [ ]
$\eta_{t,h}$	PV system temp. efficiency factor for h [ ]
β	temp. coefficient of solar cell effic. $\left[\frac{1}{°C}\right]$
$T_{a,h}$	ambient temperature for hour h [°C]
$T_{c_{ref}}$	PV cell reference temp. for hour h [°C]
η_y	PV module annual degrad. ratio $\left[\frac{1}{years}\right]$
y	years of use [years]
NOCT	normal operating cell temperature [°C]
$P(v)$	wind turbine power curve
v_h	wind speed for hour h $\left[\frac{m}{s}\right]$
$W(v)_h$	Weibull distribution function for hour h
DOD	BES system depth of discharge allowed [ ]
m	starting hour of the simulation
t_{ch}	minimum time to charge BES system [h]
t_{dch}	min. time to discharge BES system [h]
$e_{PV\,p,h}$	energy market price for PV for h $\left[\frac{€}{kW\,h}\right]$
$e_{W\,p,h}$	energy market price for W h $\left[\frac{€}{kW\,h}\right]$
$e_{c,h}$	grid electricity tariff for h $\left[\frac{€}{kW\,h}\right]$

2. HES architecture

As presented in the introduction Section, this manuscript focuses on the optimal energy management of a HES targeted to the fulfillment of the electricity request of a user load fueled by multiple RES sources, equipped with a BES and connected to the national grid. As presented in Fig. 1, two are the HES components aimed at electricity production, namely a PV system and a wind turbine (W). These two modules differ in terms of the current type of the produced energy, e.g. direct current for PV ($E_{PV,h}$) and alternating one for W ($E_{W,h}$). The dispatchment of both these energy flows within the HES, for every system operating hour h, is regulated by a charge controller which direct them towards the BES ($E_{PVB,h}$ for PV and $E_{WB,h}$ for W), the load L ($E_{PVL,h}$ and $E_{WL,h}$ respectively) or the grid G ($E_{PVG,h}$ and $E_{WG,h}$).

BES charging process requires direct current, thus the electricity produced by W has to be converted by the AC/DC converter discounting the conversion process efficiency of η_{conv} whereas the energy produced by the PV could be used without any conversion to charge the BES. The energy stored in the BES can be used in at a later stage to satisfy the user load demand ($E_{BL,h}$), but it cannot be sold to the national grid. This architecture has been defined to avoid awkward energy flows between these two HES components which determine no techno-economic benefit for the system. The BES charging and discharging process is affected by a certain efficiency, η_{ch} and η_{dch} respectively, whereas a limited portion of the electricity stored in the BES (SOC_h) is dissipated every hour (σ) due to BES self-discharge effect.

The electricity produced by the PV and W can also be used immediately to fulfill the user load request for energy. In this case, the energy flow of alternating current from W to L does not have to discount any conversion efficiency, whereas the energy generated by the PV as direct current has to be converted in alternating one through the DC/AC inverter discounting the conversion process efficiency of η_{inv} to concur to the load demand satisfaction ($E_{L,h}$).

Finally, the latest component of the proposed HES to be analyzed is the national grid, since the considering system is grid-connected. The surplus energy produced by the PV and W at every hour can be sold to G. However, G can also be leveraged to provide to the user alternating current in case of need ($E_{GL,h}$).

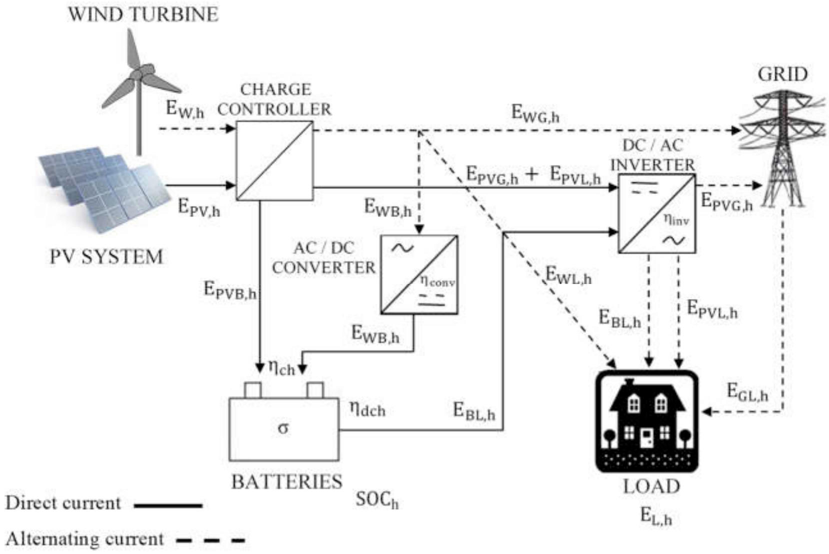

Fig. 1. Proposed HES architecture.

3. Heuristic algorithm for HES operation management

An original heuristic algorithm (HA) is proposed in this manuscript to efficiently and effectively manage the hourly energy flows of the HES presented in Section 2. The proposed HA considers the design of such HES as given and already performed, i.e. the size of each of the HES components has already been defined adopting a certain procedure, strategy or methodology (e.g. as the one proposed by [6]). The nominal power of PV (P_0), the nominal power of W (P_W) and the BES nominal capacity (K_{max}) represent the outcome of such procedure. Thus, the HA focuses on the operating phase of the HES lifecycle, defining for every operating hour h the electricity flows between the different system components. The HA is developed to adequately dispatch the energy produced by the PV and W to constantly satisfy the user demand with a proper use of the BES. Aim of the HA is to minimize the electricity purchased by the grid, while reducing as much as possible the energy loss due to the dissipation effects experienced during the BES charging/discharging cycles as well as energy conversion from AC to DC or viceversa.

The developed HA a set of sequential steps to be followed to efficiently manage the HES energy flows for every considered hour h. The required inputs for the considered hour h are the values of the energy demand of the user load ($E_{L,h}$), the BES state of charge (SOC_h) as well as the direct solar radiation (HI_h), the atmospheric temperature ($T_{a,h}$) and the wind speed (v_h) of the installation location. Considering these inputs, Eqs. (1-2) are used to determine the hourly PV and W electricity production, respectively. In particular, to evaluate $E_{PV,h}$ it is necessary to assess the PV system overall efficiently (Eq. 3) considering the PV system temperature efficiency factor (Eq. 4) and the PV cell temperature (Eq. 5). On the other hand, $E_{W,h}$ evaluation necessitate of the adoption of the Weibull distribution to estimate the wind speed through a probability density function (Eq. 6) and the power curve of the installed W ($P(v)$).

$$E_{PV,h} = \frac{HI_h \cdot \eta_{pv,h} \cdot P_0}{\eta_{mod} \cdot HR} \quad (1)$$

$$E_{W,h} = \int_0^{\infty} W(v)_h \cdot P(v)\, dv \quad (2)$$

with:

$$\eta_{pv,h} = \eta_{mod} \cdot \eta_{pc} \cdot \left[1 - (y-1) \cdot \eta_y\right] \cdot \eta_{t,h} \quad (3)$$

$$\eta_{t,h} = 1 - \beta \cdot \left(T_{c,h} - T_{c_{ref}}\right) \quad (4)$$

$$T_{c,h} = T_{a,h} + \frac{NOCT-20}{800} \cdot HI_h \quad (5)$$

$$W(v)_h = \frac{k}{s} \cdot \left(\frac{v}{s}\right)^{k-1} \cdot e^{-\left(\frac{v}{s}\right)^k} \quad (6)$$

After the evaluation of the energy produced in the hour h by both the PV and W, the HA proposes a procedure to dispatch the energy flows between the different HES components. The developed procedure considers the typical constraints of each component. For instance, concerning the BES, the minimum allowed SOC_h is limited by a lower bound, e.g. the battery depth of discharge (DOD), which aims to reduce the degradation of this module during its charging and discharging cycles. Furthermore, the energy flows are adequately managed to reach the HA target, which is the minimization of electricity purchased by the grid as well as the reduction of the energy losses due to dissipation effects during BES charging/discharging and energy conversion from AC to DC or viceversa. To meet this goal, the load energy demand is satisfied, in every hour h, giving the following priority to the different HES electricity sources: 1) Wind turbine; 2) PV system; 3) Battery energy storage system; 4) National grid.

On the contrary, the preference to charge the BES is given to the energy produced by the PV and then to the one provided by the wind turbine. Both these dispatchment criteria are determined by the current type between the HES components. Indeed, the electricity produced by W and the one required by the load are in alternating current, whereas PV energy production and BES charging is performed in direct current. Considering these motivations, the developed HA regulates the energy flows between the HES components using this priority scale (descending from the energy flow of maximum priority): 1)$E_{WL,h}$; 2)$E_{PVL,h}$; 3)$E_{PVB,h}$; 4)$E_{WB,h}$; 5) $E_{WG,h}$ and $E_{PVG,h}$ (identical priority).

The main strength of the described HA is represented by its ease of use. Indeed, it consider uniquely the current value of both the user load demand and the atmospheric conditions, which determine the energy produced by the RESs. Thus, no sophisticated control of the HES is needed, since the energy management and dispatching rules are constant over the entire system lifetime. Indeed, they do not depend on the considered hour of the day, atmospheric conditions, user actual demand, or electricity sale and purchase pricing. However, this aspect is also an evident limitation of the HA, which potentially miss the opportunity to achieve superior operating performance of the HES modeling its functioning with such a robust but simple approach. For this reason, the authors propose an original mixed integer linear programming (MILP) model to optimize the HA management considering all the aforementioned aspects ignored by the presented HA.

4. MILP model for HES operation optimization

A MILP model is presented in this Section to optimize the operations of the considered HES defining the best values for the energy flows between the system components to maximize its economic performance considering the multiple technical features which distinguish such HES. As for the HA, the size of the HES components have been already defined by whatsoever procedure (e.g. [6]), thus HES design is out of scope for the proposed optimization model.

The following paragraph presents the optimization model, organized in index, techno-economic parameters, decision variables, constraints (Eqs. 7-14) and objective function (Eq. 15). In particular the model considers a H consecutive hours (h=0,…,H) to perform its optimization (e.g. H=48). During these hours, the load demand and the atmospheric conditions values are well known and considered constant, due to highly reliable the short-term forecast made available by nowadays techniques and sensors. Thus, the decision variables are represented by the hourly value of the energy flows between the HES components for the current (h=0) but also future hours (h from 1 to H). Thus, the model defines the optimal combinations of current and future energy flows able to maximize the objective function fulfilling all the considered constraints. Adopting a rolling approach, while the daily hours elapse, h index reference range is increased by 1, e.g. h=1,…,H+1, suggesting the general notation h = m, …, H+m.

Concerning the constraints, Eq. 7, along with the aforementioned Eqs. 3-5, evaluate the energy supplied by the PV system at hour h and its usage to satisfy the load demand, charge the BES or to be sold to the grid. Similarly, Eq. 8 assess the energy produced by the wind turbine and how it is used within the HES at hour h. Eq. 9 ensures that the load energy demand would be fulfilled in every hour considering the different options for its supply (PV, W, G, B) as well as the energy loss due to conversion and discharging processes. The BES SOC is represented by Eq. 10 and it is equal to the one of the previous hour corrected by the BES self-discharge, energy input (from PV and/or W) and energy output (to load). Eqs. 11-12 limit the SOC considering the DOC suggested by the BES manufacturer to ensure the expected lifetime to this HES component. Finally, Eqs. 13-14 limit the maximum input and output current which charge and discharge the BES considering the technical feature of this energy storage system and preventing improper usage which could significantly affect its functioning.

The objective function (Eq. 15) aims to minimize the operating cost over the considered time horizon h = m, …, H+m (e.g. H=48) determined by purchased energy by the grid at the hourly variable price $e_{c,h}$ but also by the energy sold to the grid at the hourly variable prices $e_{PV\,p,h}$ and $e_{W\,p,h}$ respectively produced by PV and W. This objective function aims to accurately evaluate the real conditions of the energy market which could have a tremendous effect on the management strategy of the HES electricity hourly flows between all the system components, BES charging and discharging cycles included. The next Section 5 proposes the case study selected to test and validate such optimization model.

Index

h = m, …, H+m daily hour index

Parameters

- HES component sizes:
  P_0, P_W, K_{max};
- Hour dependent load demand and atmospheric conditions:
  $E_{L,h}$, HI_h, $T_{a,h}$, v_h $\forall h$;
- Technical features of the HES components:
  m, η_{ch}, η_{dch}, σ, η_{inv}, η_{conv}, HR, η_{mod}, η_{pc}, β, $T_{c_{ref}}$, η_y, y, NOCT, DOD, t_{ch}, t_{dch}, P(v);
- Hour dependent electricity sale and purchase price:
  $e_{PV\,p,h}$; $e_{W\,p,h}$; $e_{c,h}$ $\forall h$;

Decision variables

$E_{PVL,h}$; $E_{PVB,h}$; $E_{PVG,h}$; $E_{WL,h}$; $E_{WB,h}$; $E_{WG,h}$; $E_{BL,h}$; $E_{GL,h}$; $SOC_h \geq 0$ $\forall h$

Constraints

$$E_{PVL,h} + E_{PVB,h} + E_{PVG,h} = \frac{HI_h \cdot \eta_{pv,h} \cdot P_0}{\eta_{mod} \cdot HR} \quad \forall h \tag{7}$$

$$P(v_h) = E_{WL,h} + E_{WB,h} + E_{WG,h} \quad \forall h \tag{8}$$

$$E_{L,h} = E_{PVL,h} \cdot \eta_{inv} + E_{BL,h} \cdot \eta_{inv} \cdot \eta_{dch} + E_{WL,h} + E_{GL,h} \quad \forall h \tag{9}$$

$$SOC_h = SOC_{h-1} \cdot (1-\alpha) + E_{PVB,h} \cdot \eta_{ch} + E_{WB,h} \cdot \eta_{ch} \cdot \eta_{conv} - E_{BL,h}/\eta_{dch} \quad \forall h \tag{10}$$

$$SOC_h \leq K_{max} \quad \forall h \quad (11)$$
$$SOC_h \geq (1 - DOD) \cdot K_{max} \quad \forall h \quad (12)$$
$$E_{PVB,h} + E_{WB,h} \cdot \eta_{Conv} \leq K_{max}/t_{ch} \quad \forall h \quad (13)$$
$$E_{BL,h}/\eta_{dch} \leq K_{max}/t_{dch} \quad \forall h \quad (14)$$

Objective function

$$\min \sum_{h=m}^{H+m}(E_{GL,h} \cdot e_{c,h}) - \sum_{h=m}^{H+m}(E_{PVG,h} \cdot \eta_{inv} \cdot e_{PVp,h}) - \sum_{h=m}^{H+m}(E_{WG,h} \cdot e_{Wp,h}) \quad (15)$$

5. Case study

To test, validate and compare the developed HA and MILP, this Section presents a case study of a domestic load whom electricity request is fulfilled by the described HES. The user load is represented by a residential building in which several households live located in the suburban area of Munich (Germany). The installation location is distinguished by both irradiation and wind speed remarkable potentials as presented by Fig. 2a and 2b, respectively their monthly average values and daily trend in a certain month (i.e. July).

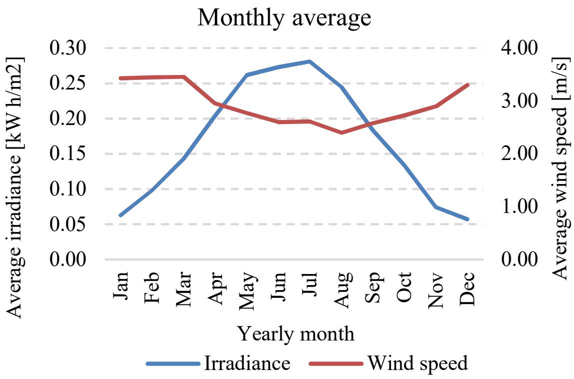

Fig. 2a. Monthly average value of irradiance and wind speed of the installation location.

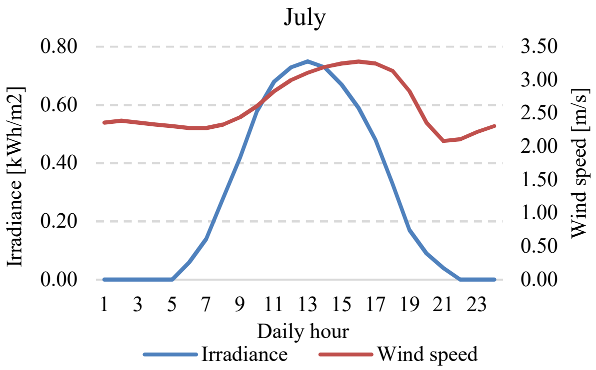

Fig. 2b. Daily trend in July of irradiance and wind speed of the installation location.

Similarly, concerning the electricity demand, the consumption peak is reached during the winter months since the location temperature is severe during this portion of the year, e.g. maximum average electricity demand 2.6 kWh in December. Focusing on the economic aspects of the HES operations, the current regulation framework, energy market and electricity providers in the considered locations determine the following prices for electricity trade purpose. Table 1 summarizes the three time slots during the day which identify high, medium or low energy market demand, as well as the respective electricity purchase price by user for such user category (residential users with standard energy requirement).

Table 1. Energy market time slots and electricity purchase price by user.

Slot name	Day & time slot	Purchase price [€/kWh]
F1	mon-fri 8am to 7pm	0.332
F2	mon-fri 7am to 8am & 7pm to 11pm sat 7am to 11pm	0.258
F3	mon-sat 11pm to 7am sun all	0.258

Concerning the electricity selling price to grid, respectively for energy produced by PV and W, these prices vary not only over the time slots during the day but also over the different months. The values of the other techno-economic parameters adopted in Eqs. 1-15 are not listed in this manuscript for sake of brevity. However, the used values are the one presented in [6] and can be easily obtained from this document. All the overrepresented input data are highly dependent from the considered month, thus a proper assessment of the HES operation management should be performed considering different scenario of such type. For this reason, the developed HA and MILP have been tested considering 5 different weeks over the year, one for each of the following months: January, May, July, August and

October. For July, in particular, a cloudy week and the correspondent atmospheric data have been adopted to stress as much as possible the potential of the developed HES operation management methods. The next Section 6 proposes the results obtained for the aforedescribed case study.

6. Results and discussion

This Section presents the results obtained adopting both the developed HA and MILP to manage the HES operation, e.g. defining the hourly energy flows between the components, for each of the identified month, in particular one representative week per month. For each week, the objective function value has been evaluated for both HA and MILP, which should be as low as possible since it is equal to the sum of operative costs (electricity purchase from grid) minus the sum of operative revenues (electricity sale to grid). Table 2 summarizes these results. MILP outperforms HA improving the economic performance of HES operations by remarkable values, which vary between 4% and 127% depending on the month considered.

Table 2. Economic performance of HES operations managed by HA and MILP (weekly time horizon).

Month	HA [€/week]	MILP [€/week]	Improvement [%]	Improvement [€/week]
January	0,15	-0,19	127%	0,34
May	-2,58	-2,69	4%	0,11
July (cloudy)	5,25	4,65	13%	0,60
August	6,26	5,53	12%	0,93
October	7,68	6,90	10%	0,78

Focusing on the cloudy week of July considered in this case study, the remarkable economic performance of the HES operations managed by the MILP is determined by the reduction of the electricity purchased during peak price time slot (e.g. time slot F1). As presented by the following Table 3, MILP management requires to purchase just 15% of energy during F1 (8.3 kWh), compared to 34% determined by HA management (18.6 kWh).

Table 3. Electricity purchased in different time slots for July cloudy week, comparison between HA and MILP operation management.

	HA		MILP	
	[kWh]	[%]	[kWh]	[%]
Electricity purchased during time slot F1	18,6	34%	8,3	15%
Electricity purchased during time slot F2-F3	36,8	66%	47,9	85%
Total electricity purchased during week	55,4	100%	56,2	100%

The remarkable performance obtained by the MILP compared to HA is enabled by the leveraging of the forecast of both atmospheric conditions and user demand as well as its comparison to electricity purchasing price which varies over the different time slots. Fig. 3 presents for the same July week the battery SOC trends over the different hours of two consecutive days determined by HA and MILP. As it is possible to notice, MILP outperforms HA since it does not use the energy stored in the BES to fulfill the user load during those hours in which the electricity purchasing price is low (F2-F3 time slot). On the contrary, MILP exploits the short term forecast of the user demand to save this free energy to be later used during peak prices (F1 time slot). As shown by Fig. 5, the absolute energy quantity retrieved from the BES to satisfy the load during F1 time slot is significantly higher in the MILP management compared to the HA one (10.3 kWh and 8.6 kWh respectively).

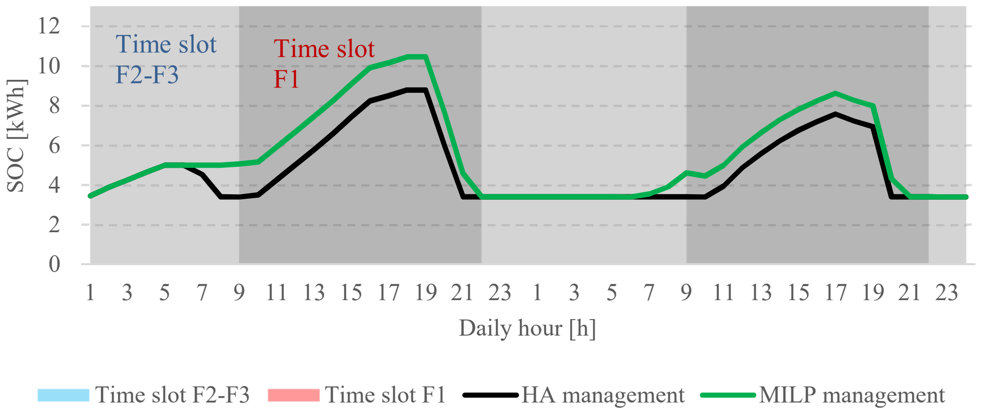

Fig. 3. BES management (SOC) determined by HA and MILP in relation to the electricity purchase time slots, July cloudy week.

Finally, the benefit of considering short term forecast of both atmospheric conditions and load demand to efficiently manage the HES operations is discussed in detail considering the January week proposed in Fig. 4. Both HA and MILP limit to 0 the energy purchased from the grid, however the battery SOC management is significantly different, considering the trend of the electricity produced by PV and W (green bars) as well as the load consumption (yellow bars). Indeed, during the first hours of the day (h=1,…,7) HA suggest loading the BES with the electricity produced by the RES, since the SOC is far lower the BES maximum capacity and no consumption is experienced by the load. However, this management strategy is biased by a local optimum. Indeed, the MILP which exploits the short-term atmospheric and load forecast, does not charge the BES during these hours since the user demand will be satisfied by the RES production in almost all the future hours. The energy saved by not charging the BES is sold to the grid, improving the HES economic operation profit compared to HA by the terrific value of 127%.

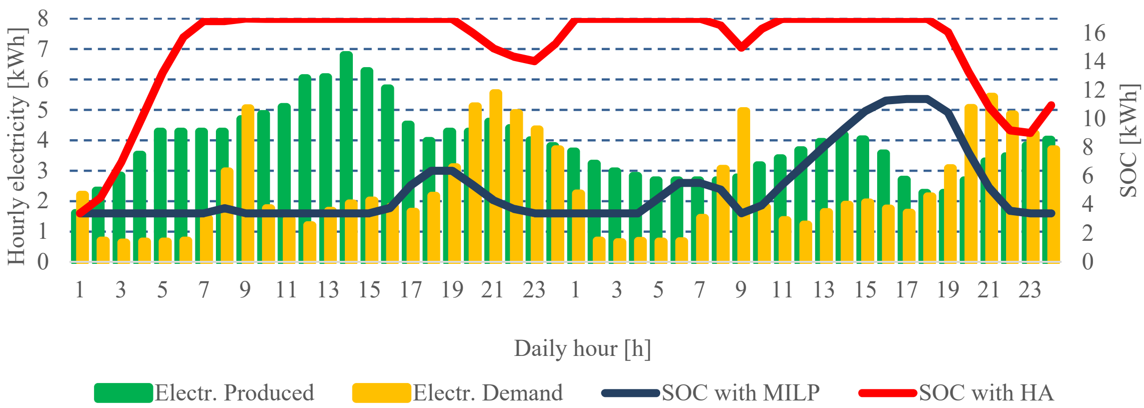

Fig. 4. Exploitation of the atmospheric and load short-term forecast to improve the HES operation management: HA and MILP comparison in January week.

7. Conclusion and further research

This manuscript investigated the field of the operation management of the HES fueled by multiple RES equipped with a BES and connected to the grid. Considering the size of the HES components as determined and constant, aim of this management strategies is to maximize the HES economic performances during the operations phase of its lifetime while fulfilling the different technical constraints which distinguish such system for electricity production. An original HA is proposed by efficiently manage such system using a robust approach. The energy flows are directed to the different HES components to minimize the energy purchased by the grid considering the current value of the environmental conditions and load demand, thus requiring almost no future data to any forecasting system. A concurrent approach is represented by a MILP which exploits the future trends of atmospheric conditions and user demand in the short-term to maximize the economic performance of the HES operations determined by the electricity trade with the energy market considering its sale and purchase prices which usually vary during the daily hour. Both these methodologies have been tested and validated through a case study of a residential building in which multiple households live located in the suburban area of Munich (Germany). The obtained results highlight how the MILP outperform HA considering the net profit achievable weekly due to electricity trade with the grid. In particular, the MILP improve the HA economic performance of the HES operation management of 18% on average over the different months of the year. The main strength of MILP is the opportunity to manage the hourly energy flows between the HES components leveraging the short-term atmospheric and demand forecast considering the different electricity sale and purchase prices over the daily hour.

Future research should adopt such methodologies, e.g. both HA and MILP, to optimize the energy flows of different HES, for instance the polygeneration systems which are devoted to the simultaneous production of both electricity and heating. Finally, the assessment of the environmental perspective into the developed procedures is highly encouraged since it could lead to different paths for the optimal HES management from the environmental point of view.

References

[1] Breyer, C., & Gerlach, A. (2013). Global overview on grid-parity. Progress in photovoltaics: Research and Applications, 21(1), 121-136.

[2] Hernández-Moro, J., & Martínez-Duart, J. M. (2013). Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renewable and Sustainable Energy Reviews, 20, 119–132.

[3] Bortolini, M., Gamberi, M., Graziani, A., Mora, C., & Regattieri, A. (2013). Multi-parameter analysis for the technical and economic assessment of photovoltaic systems in the main European Union countries. Energy conversion and management, 74, 117-128.

[4] Bortolini, M., Gamberi, M., Graziani, A., Manzini, R., & Pilati, F. (2014). Performance and viability analysis of small wind turbines in the European Union. Renewable Energy, 62, 629-639.

[5] Bortolini, M., Gamberi, M., Pilati, F., & Regattieri, A. (2018). Design and Management of Renewable Smart Energy Systems: An Optimization Model and Italian Case Study. In International Conference on Engineering Optimization. 1340-1352. Springer, Cham.

[6] Bortolini, M., Gamberi, M., Graziani, A., & Pilati, F. (2015). Economic and environmental bi-objective design of an off-grid photovoltaic–battery–diesel generator hybrid energy system. Energy conversion and management, 106, 1024-1038.

[7] Dufo-López, R., & Bernal-Agustín, J. L. (2008). Multi-objective design of PV–wind–diesel–hydrogen–battery systems. Renewable energy, 33(12), 2559-2572.

[8] Fazlollahi, S., Mandel, P., Becker, G., & Maréchal, F. (2012). Methods for multi-objective investment and operating optimization of complex energy systems. Energy, 45(1), 12-22.

[9] Ren, H., Zhou, W., Nakagami, K. I., Gao, W., & Wu, Q. (2010). Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Applied Energy, 87(12), 3642-3651.

[10] Shrouf, F., & Miragliotta, G. (2015). Energy management based on Internet of Things: practices and framework for adoption in production management. Journal of Cleaner Production, 100, 235-246.

[11] Jha, S. K., Bilalovic, J., Jha, A., Patel, N., & Zhang, H. (2017). Renewable energy: Present research and future scope of Artificial Intelligence. Renewable and Sustainable Energy Reviews, 77, 297-317.

[12] Diouf, B., & Pode, R. (2015). Potential of lithium-ion batteries in renewable energy. Renewable Energy, 76, 375-380.

[13] Yang, F., & Xia, X. (2017). Techno-economic and environmental optimization of a household photovoltaic-battery hybrid power system within demand side management. Renewable Energy, 108, 132-143.

[14] Pascual, J., Barricarte, J., Sanchis, P., & Marroyo, L. (2015). Energy management strategy for a renewable-based residential microgrid with generation and demand forecasting. Applied Energy, 158, 12-25.

[15] Motevasel, M., & Seifi, A. R. (2014). Expert energy management of a micro-grid considering wind energy uncertainty. Energy Conversion and Management, 83, 58-72.

[16] Mohamed, A., & Mohammed, O. (2013). Real-time energy management scheme for hybrid renewable energy systems in smart grid applications. Electric Power Systems Research, 96, 133-143.

[17] Kasaei, M. J., Gandomkar, M., & Nikoukar, J. (2017). Optimal management of renewable energy sources by virtual power plant. Renewable energy, 114, 1180-1188.