Design and Management of Renewable Smart Energy Systems: An Optimization Model and Italian Case Study

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Abstract. Smart and distributed energy micro-production is the new pattern for the electric energy supply, joining high service level and sustainability issues. Within such a context, the renewables, i.e. solar photovoltaic (PV), micro-wind, etc., play an increasing role as part of the source mix because of their capillary presence and the decrease of the required initial technology investments. On the contrary, the renewable intermittence is the key weakness to overcome to make a turning point to their final spread. To this purpose, hybrid energy systems join the plus of having renewable modules to the plus of having backup traditional units activated in the case of lack of energy.

This study presents and applies to an Italian rural context a linear programming model to best design and manage a local off-grid renewable smart energy system. The power system may include PV and micro-wind technologies together with a battery bank and diesel generator as the backup system. Starting from the expected average load profile, the environmental conditions and the technical features of the energy modules, the model selects the most suitable energy sources, optimizes the power rates of each unit and manages the energy flows within the system. The final goal to achieve is to minimize the levelized cost of the produced electricity (LCOE) making such a system competitive respect to fully fossil fuel based energy systems.

The aforementioned case study exemplifies the model application focusing on a remote scientific center requiring electric energy for its daily research activities. The area where the center is located is badly connected to the national grid and, actually, a fossil fuel generator is used, only, to provide electricity. An as-is vs. to-be differential analysis assesses the effect of introducing a dedicated renewable smart energy system finding its economic feasibility over a 15 year lifetime. Evidences show the convenience of exploiting the solar source, while little convenience is for micro-wind installation because of low available wind power and the increasing system complexity. Globally, the LCOE is close to 0.14 €/kWh making competitive the hybrid energy solution, close to the evident environmental benefit.

Keywords: Smart energy · Hybrid power system · Plant design optimization Renewable energy · Industrial application · Sustainability

1   Introduction and Literature Review

Renewable energies nowadays represent a clean and cheap source for electricity supply. About 24% of worldwide electricity production is fulfilled by renewable energy sources (RES), mainly by solar photovoltaic (PV) and wind power [1]. Furthermore, even nowadays some European countries (UK, Ireland and Germany) exploit PV and wind sources to supply 25% of the electricity required in their land [2, 3].

Considering the intermittent nature of RES, the power plants equipped with PV modules and WTs require a backup source to meet the electricity demand whatever the atmospheric conditions are [4]. The national grid represents a reliable but expensive alternative viable for those energy systems installed in location distinguished by an affordable connection to this public infrastructure [5, 6]. A bunch of technologies could be adopted to provide a backup source of electricity for those energy systems disconnected to the grid, e.g. off-grid. The most widespread solutions of electricity backup for energy system fueled by RES are battery energy storage systems (BES) and fuel generators [7, 8]. The former stores DC electricity produced by a power unit through a chemical principle used for energy conversion, while the latter converts the heating power of a fuel burning process into AC electricity immediately supplied to the load [9].

The integration of multiple power units fueled by RES with off-grid backup sources define the so-called hybrid energy systems (HESs). The aforementioned characteristics of these systems make HES a proper off-grid source of electricity for different contexts, e.g. isolated locations, developing countries, grid independence requirement, etc. [10]. Several literature contributions have been developed in recent years to address this topic from different perspectives.

Many Authors focus on the design of these systems. HOMER is powerful tool for HES design to determine the optimal size of its components carrying out a detailed techno-economic analysis [11]. Many different RES can be modeled and evaluated through this software such as WTs and PV arrays, BES and conventional generators [12]. Despite the advantages of using a ready-to-use tool, several researchers developed original approaches to propose a customized analysis tailored on the peculiarities of the considered HES. Simulation techniques could be of strong help to validate multiple scenarios of HES configurations distinguished by different sizes of the energy system modules [13]. The limited computational complexity of such approach is often overcome by the quality of the proposed solutions. Indeed, such techniques do not investigate the entire feasible solution space, thus they develop sub-optimal solutions for the HES design problem [14]. To overcome this limitation different authors propose the adoption of optimization techniques. These approaches aim to identify the optimal size of the different modules of such energy system to maximize the HES performances. Optimization techniques for HES design typically focuses on the energy system planning and installation rather than on its operation and management. Gonzalez et al. [15] proposes an optimization model to define the optimal size of an off-grid energy system equipped with PV, WT and BES. Their contribution focuses on the definition of the electricity storage capacity since this module is the most expensive for most of the HES. Kaabeche et al. [16] widen this approach suggesting to consider all the expenditure which occur during the entire HES lifecycle. The net present value of all these

different expenditures is compared to the total electricity produced during the HES lifecycle to evaluate the levelized cost of electricity (LCOE) [17].

The management of the hourly energy flows between the different modules and the user load is traditionally defined by a heuristic algorithm which implement ground truth criteria to seamlessly fulfill the user load demand [18]. Few Authors focus their research on HES operation and management. Aim of these researches is the development of adequate strategies to manage the hourly energy flows between the different energy system modules to fulfill the user electricity demand in whatever condition. Alnejaili et al., [19] adopt a commercial software (Matlab Simulink) to simulate the HES operation considering the atmospheric condition uncertainty and the related fluctuation of electricity production from RES. Dagdougui et al. [20] focus on the management of the BES charging and discharging process. Indeed, the depth of discharge, the inlet and outlet current and the charging cycles significantly affect the BES efficiency and expected lifetime [21].

The analyzed literature contributions suggest the strong interrelation between the design and the management problem for HES. Thus, the development of an integrated approach for the simultaneous design and management of such HES is of strong interest and could represent a relevant advance in the literature. As far as the Authors knowledge, this paper proposes one of the first contribution dealing with the integrated design and management problem for HES. The proposed manuscript considers an off-grid energy system equipped with PV modules, a small-size WT, a BES and a diesel generator to fulfill the electricity requirement of a user load. A linear programming (LP) model has been developed to optimize the size of each HES module and simultaneously define the hourly energy flows between them and the user load. The model considers the hourly profiles over the different months of the user electricity demand and of the most relevant atmospheric conditions (e.g. wind speed, temperature, irradiation, etc.).

The structure of this paper is organized as it follows. Section 2 presents the configuration of the considered HES along with the LP model developed to design and manage the energy system. Section 3 proposes the real case study adopted to test and validate the developed model. Section 4 analyzes in detail the results obtained adopting the developed optimization model to the considered case study. Section 5 concludes this paper with the most relevant remarks providing future research directions.

2   Model Presentation and Discussion

The proposed model addresses the design of a hybrid renewable energy systems operating locally without any connection to the electric national grid. The system is made of the following units:

– PV renewable energy module equipped with MPPT DC/DC unit and DC/AC inverter;
– Battery bank to store energy coming from the discontinuous sources for future supply equipped with the DC/AC inverter;
– Wind renewable energy module, i.e. typically micro-wind;

– Backup fossil fuel unit, i.e. typically a diesel engine;
– Energy load supposed to be an AC load sampled hourly;
– Bus line (AC line) and dispatching control unit managing the flows and controlling the system.

The following Fig. 1 presents a logic rationale of the system, while the Appendix lists the model notations used in the following design model.
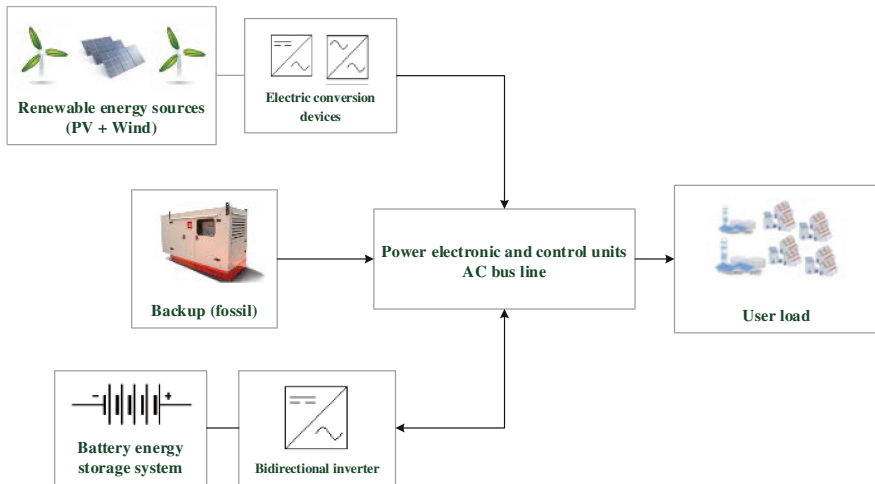

Fig. 1. Logic rationale of the off-grid hybrid energy system.

The model allows addressing the following decisions:

– Definition of the hybrid energy system structure in terms of module to install or not;
– Definition of the module size and rated power;
– Management of the hybrid energy system and expected energy flows to supply the load.

To optimally tackle the problem, the model optimizes the investment and operative annual rising cost over the system lifetime. Both the literature and the standard practice suggest the adoption of the LCOE as the objective function to optimize to fully include the introduced economic perspective. In addition, the major classes of input data feeding the model are about the load profile to supply, the environmental data, e.g. solar irradiance, wind speed, etc., the technical features and the cost data of each module.

2.1   Model Formulation

The model objective function minimizes the overall system LCOE expressed in (1)

$$
minLCOE = \frac{\Psi_0 + \sum_{j=1}^{N} \Psi_j \cdot \frac{(1+g)^{j-1}}{(1+OCC)^j}}{\sum_{j=1}^{N} \left(\sum_{h=1}^{H} E_{hj} \right) \cdot \frac{(1+g)^{j-1}}{(1+OCC)^j}} \tag{1}
$$

where Ψ_0 indicates the plant initial investment and Ψ_j is for the jth annual operative cost. Analytically:

$$
\Psi_0 = \left(C^{PV} + C^{I,PV} \right) \cdot X^{PV} + \left(C^{BES} + C^{I,BES} \right) \cdot X^{BES} + C^W \cdot X^W \tag{2}
$$

$$
\Psi_j = \left(C^{O\&M,PV} + \alpha_j \cdot C^{I,PV} \right) \cdot X^{PV} + \left(\beta_j \cdot C^{I,BES} + \gamma_j \cdot C^{BES} \right) \cdot X^{BES} + \\
C^{O\&M,W} \cdot X^W + \sum_{h=1}^{H} \left(C^{O\&M,G} \cdot \sigma_{hj}^G + C_j^{fuel} \cdot F_{hj}^G \right) \tag{3}
$$

The addenda in Eq. (2) deal with the investments in the PV modules, including the DC/DC and DC/AC inverter, the battery bank, including the DC/AC inverter, and the wind module. Equation (3) collects the annual cost for the PV, battery, wind and backup modules.

The model constraints, giving consistence to the design problem, are listed and commented below.

$$
F_{hj}^{PV} + F_{hj}^W + F_{hj}^G + F_{hj}^{BES,Out} = E_{hj} + F_{hj}^{BES,In} + F_{hj}^L \quad \forall h,j \tag{4}
$$

$$
F_{hj}^{PV} = H_{hj} \cdot \frac{X^{PV}}{H^{ref}} \cdot \eta_{hj}^{PV} \cdot \eta^{I,PV} \quad \forall h,j \tag{5}
$$

$$
F_{hj}^W = \begin{cases} 0 & \left(v_{hj} \leq v_{in} \right) \bigvee \left(v_{hj} > v_{off} \right) \\ \frac{X^W \cdot \eta^W}{v_{nom} - v_{in}} \cdot \left(v_{hj} - v_{in} \right) & v_{in} < v_{hj} \leq v_{nom} \\ X^W \cdot \eta^W & v_{nom} < v_{hj} \leq v_{off} \end{cases} \quad \forall h,j \tag{6}
$$

$$
F_{hj}^G \leq P^G \quad \forall h,j \tag{7}
$$

$$
\sigma_{hj}^G \geq F_{hj}^G / P^G \quad \forall h,j \tag{8}
$$

$$
F_{hj}^{BES,In} \leq \sigma_{hj}^{BES} \cdot \mathcal{M} \quad \forall h,j \tag{9}
$$

$$
F_{hj}^{BES,Out} \leq \left(1 - \sigma_{hj}^{BES} \right) \cdot \mathcal{M} \quad \forall h,j \tag{10}
$$

$$
SOC_{hj} = SOC_{(h-1)j} + F_{hj}^{BES,In} \cdot \eta^{BES} \cdot \eta^{I,BES} - \frac{F_{hj}^{BES,Out}}{\eta^{BES} \cdot \eta^{I,BES}} \quad \forall j, h > 1 \tag{11}
$$

$$SOC_{1j} = SOC_{Hj} + F_{1j}^{BES,In} \cdot \eta^{BES} \cdot \eta^{I,BES} - \frac{F_{1j}^{BES,Out}}{\eta^{BES} \cdot \eta^{I,BES}} \quad \forall j > 1 \tag{12}$$

$$SOC_{11} = (1 - DOD) \cdot X^{BES} + F_{11}^{BES,In} \cdot \eta^{BES} \cdot \eta^{I,BES} - \frac{F_{11}^{BES,Out}}{\eta^{BES} \cdot \eta^{I,BES}} \tag{13}$$

$$(1 - DOD) \cdot X^{BES} \leq SOC_{hj} \leq X^{BES} \quad \forall h,j \tag{14}$$

$$\sigma_{hj}^{BES}, \sigma_{hj}^{G} \text{ binary} \quad \forall h,j \tag{15}$$

$$X^{PV}, X^{BES}, X^{W}, F_{hj}^{PV}, F_{hj}^{W}, F_{hj}^{G}, F_{hj}^{BES,Out}, F_{hj}^{BES,In}, F_{hj}^{L}, SOC_{hj} \geq 0 \quad \forall h,j \tag{16}$$

Equation (4) balances the energy flows on the system AC bus line, while Equations from (5) to (10) define and limit the energy flows from each energy source. Particularly, (5) defines the energy flow coming from the PV module, function of the hourly solar irradiance, (6) models the wind module power curve between the cut-in and the cut-off wind speed, (7) sets an upper limit to the energy from the backup module, (8) to (10) correlate the energy flows to the binary variables indicating the hourly use of the battery bank and the backup module. Furthermore, Equations from (11) to (14) set the battery bank state of charge at the end of each hour of the year linking it to the energy flows of that hour and the state of charge of the previous hour. Finally, Eqs. (15) and (16) define the model binary and continuous variables.

The proposed optimization model belongs to the binary linear programming class, it includes $2 \cdot H \cdot N$ binary variables, $7 \cdot H \cdot N + 3$ continuous variables and $10 \cdot H \cdot N$ linear constraints. To solve the model a general purpose mixed integer linear programming solver is usable optimizing both the module size and the energy flow management and dispatching. The following section show-cases the model use to design the off-grid hybrid renewable energy system of a remote scientific research building located in the north of Italy.

3 Case Study

Figure 2 shows the annual energy demand profile of a scientific research building located in the north of Italy in a remote area not connected to the national grid. Daily energy peaks are associated to low energy demand during the night.
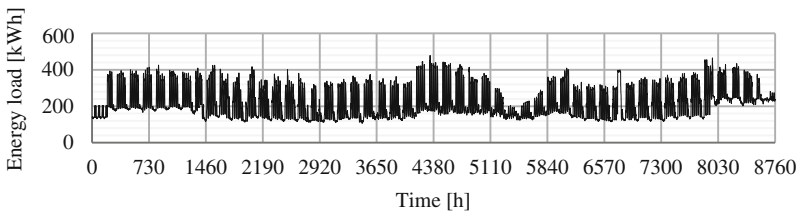

Fig. 2. Energy load for a reference year (vertical grid lines separate the months).

The geographic location is known for mid-irradiance, i.e. 400 to 600 W/m^2 on average, and mid-low wind speed, i.e. 3 to 4 m/s on average (see Figs. 3 and 4).
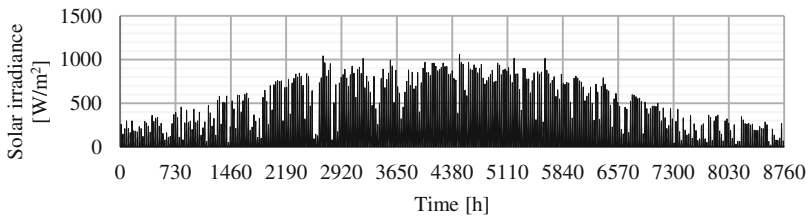

Fig. 3. Annual distribution of the solar irradiance (vertical grid lines separate the months).

Actually, the energy demand is satisfied through a set of diesel engines sized to supply the energy peaks. No load shifting and shaving is allowed due to the critic and not delayable research activities requiring electric energy. To mark a turning point in the energy supply of the research center a preliminary feasibility study to assess the feasibility of installing an off-grid hybrid renewable energy system is done. At first a scouting phase of the market allows estimating the input cost and technical data to feed the optimization model. The detailed list of them is omitted here for brevity and it is available upon request to the Authors.
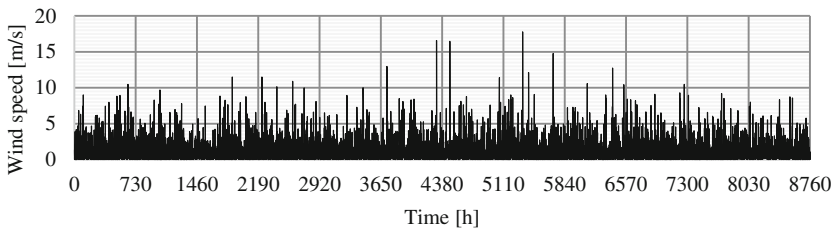

Fig. 4. Annual distribution of the wind speed (vertical grid lines separate the months).

The optimization model is run considering a lifetime of 20 years so that 1,576,803 variables rise with 1,752,000 constraints. The model, together with the input data, are coded in AMPL language and processed adopting Gurobi Optimizer© v.5.5 solver. An Intel® CoreTM i7-3770 CPU @ 3.40 GHz and 16.0 GB RAM workstation is used. The average solving time is approximately of 6 h. The key outcomes are discussed in the following.

4   Results and Discussion

This Section provides a detailed analysis of the results obtained through the application of the developed LP model for HES design and management to the presented case study. Table 1 proposes the optimal HES configuration defined by the LP model. This

solution suggests to not install any WT nor BES. The former decision is determined by the atmospheric features of the selected installation location. The average wind speed of 3.2 m/s is too limited to fully exploit the generation capacity of any WT, even the ones distinguished by small sizes. Concerning the BES, the model does not suggest to install any electricity storage system. The relevant capital cost required for its purchase does not make this backup solution economically profitable. On the contrary, the model proposes to install a 480 kW diesel generator as a reliable source of electricity independent from any atmospheric condition. The economic performances of the HES are further improved through the installation of a 338 kWp PV plant. The remarkable average irradiation of the installation location (970 W/m^2) enables to produce clean electricity at a limited operating cost beyond the purchase expenditure.

Table 1. Proposed HES design and module sizes.

HES module	Module size
PV	338 kWp
Diesel generator	480 kW
BES	0 kWh
WT	0 kW

The proposed configuration for the considered HES is distinguished by the convenient LCOE value of 0.13 €/kWh. Compared to the electricity purchase price from the national grid, the proposed HES enables to save 18% of the total expenditures occurred during the entire energy system lifetime. Furthermore, the cost structure of such system has an extremely low risk since most of the financial expenditures are related with the HES operation. As proposed by Fig. 5, the initial investment required to purchase, transport, engineer and install the system components represents just 11% of the total cost. This characteristic significantly reduces the financial exposure and the economic risk of the initiative. Indeed, the required initial capital is limited compared to the yearly cash flows which occur over the HES entire lifetime. Most of this operating costs are determined by the generator fuel purchase (84% of the total cost), whereas the
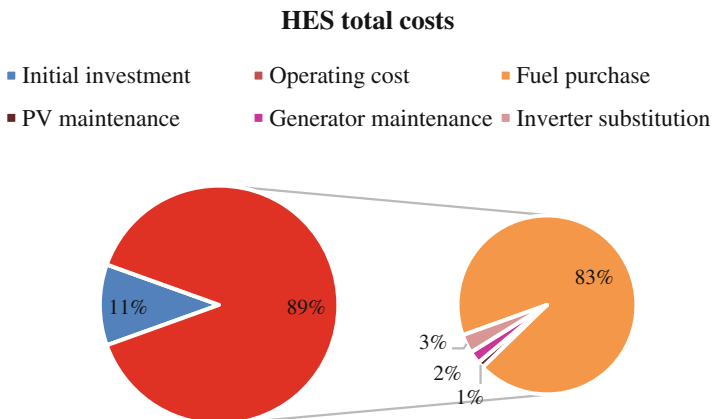
HES total costs

- Initial investment
- Operating cost
- Fuel purchase
- PV maintenance
- Generator maintenance
- Inverter substitution

Fig. 5. HES total cost partition.

PV maintenance, the generator maintenance and the inverter substitution represents a modest portion of the LCOE (overall 6%).

Focusing the analysis on the user load, of major interest is the source adopted to fulfill its electricity demand. The designed off-grid HES is equipped with PV modules and a diesel generator with no energy storage opportunity. For this reason, the user load has to be supplied in every hour by the PV modules and/or the generator. This inter-relation is strongly affected by the considered hour and day over the year. Indeed, both the PV supply capacity and the user demand depend on these characteristics. The electricity produced by the PV modules is available only during the daylight and it is much higher in summer months, whereas the profile of the electricity required by the load is the one typical of an office building. The following Figs. 6a and 6b present the electricity supplied to the load by the two aforementioned sources during two days of opposite seasons of the year, e.g. winter and summer. During winter, the PV provides a limited contribution to fulfill the load demand since it produces electricity for 8 h per day only, whereas the generator operates 24/7 since the PV cannot meet, alone, the user requirement. On the contrary, during summer the PV modules generates electricity for 14 h per day and is able to fulfill alone the load requirement for 6 h per day. In these
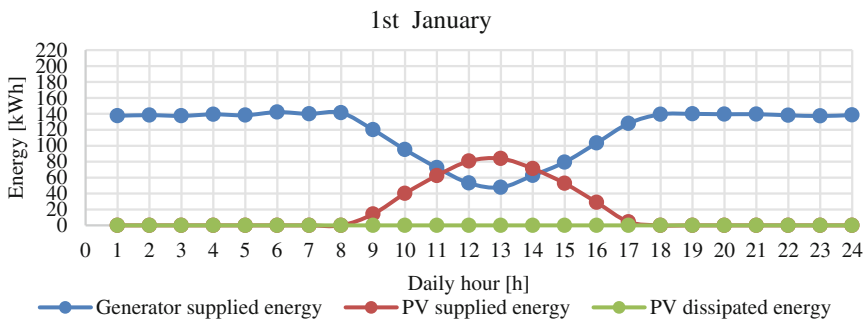

Fig. 6a. Electricity supply to the user load by the difference HES modules, winter scenario.
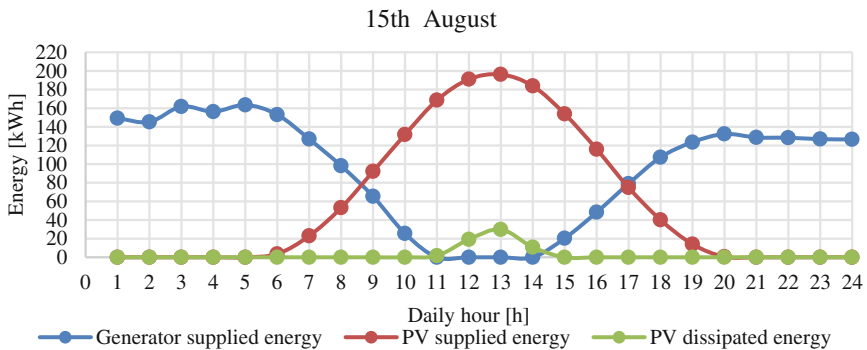

Fig. 6b. Electricity supply to the user load by the difference HES modules, summer scenario.

hours the PV production capacity is so high that the HES is forced to dissipate the surplus electricity produced by the PV due to the off-grid configuration.

5   Conclusions

This paper proposes an original optimization model targeted at the design and management of HES. This research considers an off-grid energy system equipped with PV modules and small-size WTs to fully exploit the RES available in the installation location. Furthermore, a battery bank provides the system with an adequate storage capacity whereas a diesel generator is a fundamental backup source to ensure the HES reliability whatever the atmospheric conditions are. An original LP model is developed to simultaneously optimize the sizes of the different HES modules and the electricity flows between them and the user load. Indeed, HES design and management are strongly interrelated decisions which affect each other. As far as the author knowledge, this combined approach is one of the first proposed in the literature. The benefit of this technique is quantitatively measured by the LP model objective function, e.g. LCOE. This indicator is the net present values of all the costs which occur during the entire HES lifetime considering the different phases, e.g. purchase, transport, engineering, installation, operation, maintenance, decommission and end of life treatments. The model is tested and validated through a real case study which represents a research center located in a remote Italian location. The required input data deal with the installation and operating costs as well as with the hourly profiles of the electricity demand and of the atmospheric conditions, e.g. wind speed, temperature, irradiation, etc. The results obtained through the LP application suggest to fully exploit the diesel generator and the PV modules but to not install any WT nor BES. This system configuration, along with a proper energy flow management strategy defined by the LP model, enables to achieve remarkable economic performances, e.g. LCOE value 18% lower than the electricity market price.

Future research should develop a sensitivity analysis focused on the most relevant LP model parameters, e.g. fuel price, BES charging/discharging process, PV efficiency, etc. Furthermore, the proposed model should be adopted to design and manage other HES located in different geographical locations, in particular the one distinguished by relevant profiles of wind speed.

Appendix

List of the model notations with units.

Indices

h Index for hours $h = 1, \ldots, H$

j Index for lifetime years $j = 1, \ldots, N$

Variables

$F_{hj}^{BES,In}$	Battery bank charge energy flow for hour h of year j (kWh)
$F_{hj}^{BES,Out}$	Battery bank discharge energy flow for hour h of year j (kWh)
F_{hj}^{G}	Backup module energy flow for hour h of year j (kWh)
F_{hj}^{L}	Excess of energy for hour h of year j (kWh)
F_{hj}^{PV}	PV module energy flow for hour h of year j (kWh)
F_{hj}^{W}	Wind module energy flow for hour h of year j (kWh)
SOC_{hj}	Battery bank state of charge for hour h of year j (kWh)
X^{BES}	Battery bank size (kW)
X^{PV}	PV module size (kW)
X^{W}	Wind module size (kW)
σ_{hj}^{BES}	1(0) if the battery bank is charged (discharged) at hour h of year j
σ_{hj}^{G}	1 if the backup module is used at hour h of year j, 0 otherwise

Parameters

C^{BES}	Battery bank unitary cost (€/kW)
C_{j}^{fuel}	Backup unit fossil fuel cost for year j (€/kWh)
$C^{I,BES}$	Battery bank inverter unitary cost (€/kW)
$C^{I,PV}$	PV module inverter unitary cost (€/kW)
$C^{O\&M,BES}$	Battery bank operating & maintenance unitary cost (€/kW)
$C^{O\&M,G}$	Backup module operating & maintenance unitary cost (€)
$C^{O\&M,PV}$	PV module operating & maintenance unitary cost (€/kW)
$C^{O\&M,W}$	Wind module operating & maintenance unitary cost (€/kW)
C^{PV}	PV module unitary cost (€/kW)
C^{W}	Wind module unitary cost (€/kW)
DOD	Battery bank depth of charge (%)
E_{hj}	Energy load for hour h of year j (kWh)
g	Inflation rate (%)
H_{hj}	Solar irradiance at hour h of year j (W/m^2)
H_{ref}	Reference solar irradiance (W/m^2)
OCC	Opportunity cost of capital (%)
P^{G}	Backup module size (kW)
v_{hj}	Wind speed at the blade level at hour h of year j (m/s)
v_{in}	Wind module cut-in speed (m/s)
v_{nom}	Wind module nominal speed (m/s)
v_{off}	Wind module cut-off speed (m/s)
α_{j}	1 if the PV module inverter is reconditioned at year j, 0 otherwise

β_j	1 if the battery bank inverter is reconditioned at year j, 0 otherwise
γ_j	1 if the battery bank is reconditioned at year j, 0 otherwise
η^{BES}	Overall efficiency of battery bank (%)
$\eta^{I,BES}$	Overall efficiency of battery bank inverter (%)
$\eta^{I,PV}$	Overall efficiency of PV module inverter (%)
η^{PV}_{hj}	Overall efficiency of PV module at hour h of year j (%)
η^W	Overall efficiency of wind module (%)

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