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Management of a hybrid renewable power plant supplying an isolated rural load within a changing environment

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Abstract: Often, authors deal with the sizing issue of hybrid power plants on horizons of several years. Proposed approaches are certainly essential to optimize energy costs. However, these solutions cannot remain optimal throughout the life cycle of the plant due to the inevitable evolution of the number of households, their consumption profiles, and possible degradation of a part of the plant. In this paper, an efficient management strategy of a sized hybrid renewable system is developed. It is based on the scheduling of the different resources of the plant. The main aim is to minimize the generated energy cost while ensuring an optimal quality of service and taking into account the evolution of the environment. The scheduling issue was modeled as a constrained quadratic problem and solved using the interior-point-convex algorithm. To show the effectiveness of the approach, several scenarios representing the changing context have been developed and implemented on an existing power plant. Obtained results were compared with the case of energy dispatch without management and significant energy cost savings was noticed. This work provides an efficient decision aid tool for the microgrid manager and fits well with the general policy of smart grids.

Key words: Energy management, scheduling problem, hybrid power system, PV/wind turbine/battery/diesel power system, renewable energy

1. Introduction

Providing electrical power for isolated areas appears as a serious problem from a technical and economic point of view. The small number of households and the distance from the public distribution grid makes their connection very complex. This is due to constraints related to bad weather, wind, and high temperature gradients between seasons, days, and nights. All around the world, diesel generators are often used to supply these isolated areas, but while operating with a low load factor (less than 50% of rated power), this leads to high maintenance costs, low combustion, and a high level of pollution and certainly causes the reduction of their life cycle [1]. This situation makes them uncompetitive. In this regard, hybrid renewable power plants composed of various hybrid energy sources can serve as a good alternative to reach the desired objectives efficiently and economically.

Several configurations of hybrid systems are described in the literature. One can mention here some current combinations; for example, Kumar and Palwalia presented a technical review of hybrid PV/wind turbine generation in standalone mode in India [2]. Ruther et al. discussed the potential of PV/diesel systems in the Brazilian Amazon [3]. Kaabeche et al. implemented an optimal sizing of a PV/wind turbine/battery system in Algeria [4]. Ali performed a techno-economic analysis of a PV/wind turbine/fuel cell/battery located at a desert

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safari camp in the UAE [5]. Siddique et al. proposed an optimal integration of PV/wind with an existing diesel power plant into the public grid [6]. Tabatabaei et al. presented a synthesis of alternative fuel technologies [7].

To the best of the authors' knowledge, most research deals with the sizing issue of hybrid renewable power plants on horizons of several years [8]. Obtained results are certainly essential to minimize energy costs. Nevertheless, these cannot remain optimal along the life cycle of the plant. This is due to the inevitable evolution of the number of households (usually increasing), their consumption profiles, and possible degradation of a part of the plant. In this work, we are interested in developing a management strategy of an existing PV/wind turbine/diesel generator/electrochemical battery hybrid system sized to supply a standalone site of a set of rural households, located in the area of the Center for Renewable Energy Development (CDER) situated in Bousmail, Algeria [9]. The proposed strategy is based on the scheduling of the different sources of this micropower plant. The main purpose is to minimize the generated energy cost and allow an optimal quality of service, while taking into account the evolution of the environment, including number of consumers, consumption profile, and degradation of sources. The scheduling issue is modeled as a constrained quadratic problem and solved using the interior-point-convex algorithm. Several scenarios representing the changing environment are developed and tested on a real case. Simulation results are based on available wind and solar energy data forecasted in advance in this area.

The rest of the paper is organized as follows. In the next section, we summarize the characteristics of the micro renewable system considered for our study. Then, in Section 3, we propose the mathematical modeling of the scheduling problem. Section 4 follows with a description of the proposed solving methodology. In Section 5, we report the results of different scenarios of simulation applied on a real case and, finally, in Section 6, we give some conclusions and prospects for future research.

2. System description

2.1. Hybrid system configuration

The micro renewable hydride system considered herein is located in the area of the CDER situated in Bousmail, Algeria. It includes a wind turbine, 10 photovoltaic panels, an electrochemical battery, and a diesel generator (Figure 1).

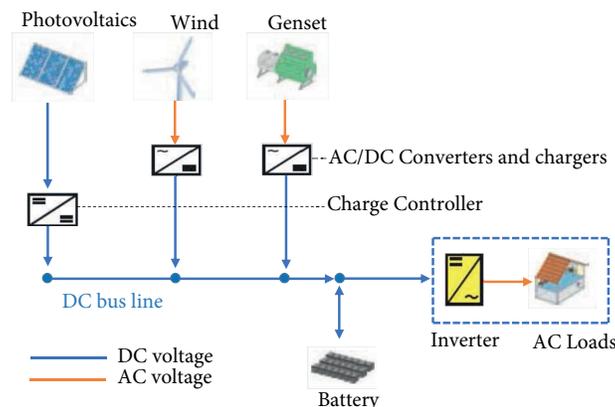


Figure 1. The CDER micro hybrid renewable system.

The purpose of this system is to supply an isolated load with energy from the combination of wind and photovoltaics. The load and both wind power and solar radiation are functions of time (day, season, and year).

The balance between energy intake from each source and the demand (load) is not always ensured. The lack of energy can be compensated by the insertion of an electrochemical storage battery and a diesel group if necessary.

The diesel generator is intentionally oversized; indeed, the power plant should meet the energy demand over a horizon of 10 years while taking into account the evolution of the number of households.

We can appreciate the daily energy produced by the hybrid generator (Figure 2). One can notice the complementarity between wind and PV sources of energy production. The continuous nature of the availability of energy throughout the day is highly satisfactory for the attenuation of the part allocated to battery storage.

2.2. Energy demand profile

Figure 3 illustrates the daily electrical energy demand of a typical rural household in Algeria. The most frequently used equipment are refrigerator, lighting, television, water pump, and electrical fan. We denote the peak period between 1700 and 2100 hours.

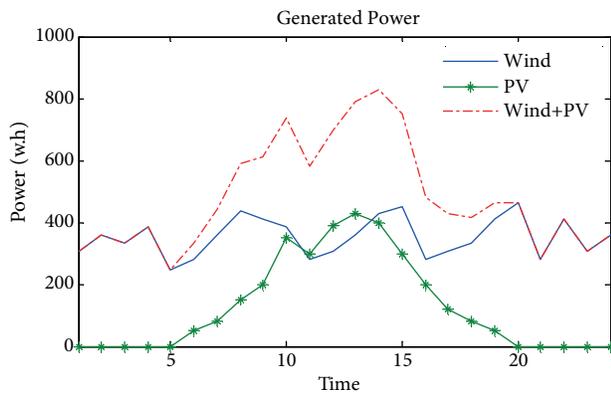


Figure 2. Hourly wind and PV potential of the site.

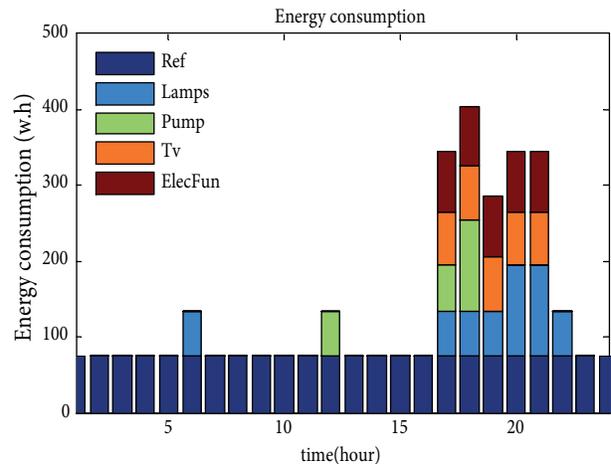


Figure 3. Energy demand profile of a rural household.

3. Mathematical model

3.1. PV and wind models

PV and wind power generation depend strongly on weather conditions. The work in [10,11] shows the most used analytical models to calculate the output of wind and photovoltaic generator power. In this paper, we use data forecast a day in advance (Figures 2 and 3).

3.2. Diesel generator model

The diesel generator is modeled herein by its fuel cost given by the constructor

$$C(P_{Diesel}) = \begin{cases} a \times P_{Diesel}^2 + b \times P_{Diesel} + c & \text{if } P_{Diesel} \neq 0 \\ 0 & \text{if } P_{Diesel} = 0 \end{cases} \quad (1)$$

where a (\$/(kW)²h), b (\$/kWh), and c (\$/h) are cost coefficients.

3.3. Battery model

Depending on the PV and wind energy production and the load power requirements, the state of charge of the battery can be calculated from the following equations.

3.3.1. Charging state

When the total output power of the wind turbine and the PV panels is greater than the power demand, the battery is in charging state. The state of charge at time t is given by [12]:

$$SOC(t) = SOC(t - 1) \times (1 - \sigma) + P_{Bat-Char}(t) \quad , \quad (2)$$

where:

$$P_{Bat-Char}(t) = (P_{Tot}(t) - P_{Load}(t)/\eta_{Inv}) \eta_{Bat}, \quad (3)$$

$$P_{Tot}(t) = P_{Wind}(t) + P_{PV}(t) + P_{Diesel}(t) \quad . \quad (4)$$

$SOC(t)$ and $SOC(t-1)$ are the state of charge of the battery bank at time t and $t-1$.

$P_{Bat-Char}(t)$, P_{Wind} , P_{PV} , P_{Diesel} , and P_{Load} are respectively the battery charge power, wind power, photovoltaic power, diesel power, and power demand.

σ , η_{Inv} , and η_{Bat} are the hourly self-discharging rate, the efficiency of the inverter, and the charge efficiency of the battery bank.

3.3.2. Discharging state

On the other hand, the battery is in discharging state:

$$SOC(t) = SOC(t - 1) \times (1 - \sigma) + P_{Bat-Dis}(t) \quad , \quad (5)$$

$$P_{Bat-Dis}(t) = (P_{Load}(t)/\eta_{Inv} - P_{Tot}(t)) \quad . \quad (6)$$

$P_{Bat-Dis}$ is the battery discharge power.

4. Problem formulation

The problem is formulated as an optimum management strategy with the context of energy cost minimization, while ensuring optimal balance between available power and load. The following assumptions are made:

- The energy demand profile is the same for all the rural households.
- The initial energy level of battery storage is known in advance.

1. Objective function

The objective function “Cost” is a quadratic cost function that includes the produced energy cost of each part of the power plant, and must satisfy the rural load.

Minimize Cost

Where:

$$Cost = \sum_{t=1}^{24} \left(\begin{array}{l} P_{Wind}(t) \times C_{Wind} + P_{PV}(t) \times C_{PV} + C((P_{Diesel}(t), t) + P_{Bat-Dis}(t) \times C_{Bat-Dis} \\ -P_{Bat-Char}(t) \times C_{Bat-Char} - E_{Ex}(t) \times C_{Ex} + E_{Und}(t) \times C_{Und} \end{array} \right) \quad (7)$$

Subject to:

4.1. Constraints

- Power balance:

$$\sum_{t=1}^{24} (P_{Wind}(t) + P_{PV}(t) + P_{Diesel}(t) + P_{Bat-Dis}(t) + E_{Und}(t)) = P_{Load}(t) + P_{Bat-Char}(t) + E_{ex}(t) \quad (8)$$

-Diesel generation limits

$$P_{Diesel}(t) \leq P_{Diesel-max} \quad (9)$$

- State of charge limits:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (10)$$

-Maximal discharge limits in each period considering the state charge in period t-1

$$P_{Bat-Dis}(t) \leq SOC(t - 1) \quad (11)$$

-Maximal charge limits in each period considering the state charge in period t-1

$$P_{Bat-Char}(t) \leq SOC_{max} - SOC(t - 1) \quad (12)$$

E_{Ex}, E_{Und} are excess and undelivered energy, respectively.

$C_{Wind}, C_{PV}, C_{Bat-dis}, C_{Bat-char},$ and C_{Ex} are prices of each kind of energy source.

5. Methodology

To solve the formulated problem, the interior-point-convex algorithm is used. This technique is very advantageous in solving the problem of finding a vector x that minimizes a quadratic function, possibly subject to linear constraints, expressed as: Minimize $f(x)$

$$\text{s.t. } g(x) = 0 \text{ (equality constraints)} \quad (13)$$

$$h_l < h\{x\} < h_h \text{ (inequality constraints)}$$

We need to transform the inequality constraints into equality constraints by introducing slack variables $s_l, s_h,$

$$\begin{aligned} &Min f(x) \\ &\text{s.t.} \\ &g(x) = 0 \\ &h(x) - s_l - h_l = 0 \\ &h(x) + s_h - h_h = 0 \\ &s_l, s_h > 0 \end{aligned} \quad (14)$$

The nonnegative conditions on slack variables in Eq. (14) can be treated by appending the logarithmic barrier functions to the following objective.

$$f_{\mu} = f(x) - \mu \cdot \left(\sum_{j=1}^m \ln(s_l)_j + \ln(s_h)_j \right) \quad (15)$$

Assume there are n state variables x and m inequality constraints, and the barrier parameter μ is a positive number that is enforced to decrease towards zero iteratively.

Based on Fiacco and McCormick's theorem [13], as μ tends towards zero, the solution of the subproblem $x(\mu)$ approaches the solution of Eq. (14). The resultant Lagrangian function of the subproblem with barrier functions is:

$$L_\mu = f(x) - \gamma_g^T \cdot g(x) - \mu_l^T \cdot (h(x) - s_l - h_l) + \mu_h^T \cdot (h(x) + s_h - h_h) - \gamma \cdot \left(\sum_{j=1}^m \ln(s_l)_j + \ln(s_h)_j \right) \tag{16}$$

where $\gamma_g^T, \mu_h^T, \mu_l^T$ are Lagrangian multipliers for constraints in Eq. (14), respectively.

Thus, the stationary point of Eq. (15) is the optimal solution of the subproblem, which satisfies Karush–Kuhn–Tucker (KKT) first-order conditions [14]:

$$\begin{aligned} \nabla_x L_\mu &= \nabla f(x) - \nabla g(x)^T \cdot \gamma_g - \nabla h(x)^T \cdot (\mu_l + \mu_h) = 0 & \text{(a)} \\ \nabla_{s_l} L_\mu &= \mu_l - \mu \cdot s_l^{-1} \cdot e = 0 \Rightarrow s_l \cdot \mu_l = \mu \cdot e & \text{(b)} \\ \nabla_{s_h} L_\mu &= \mu_h - \mu \cdot s_h^{-1} \cdot e = 0 \Rightarrow s_h \cdot \mu_h = \mu \cdot e & \text{(c)} \\ \nabla_{\gamma_g} L_\mu &= -g(x) = 0 & \text{(d)} \\ \nabla_{\mu_l} L_\mu &= -(h(x) + s_l - h_l) = 0 & \text{(e)} \\ \nabla_{\mu_h} L_\mu &= h(x) + s_h - h_h = 0 & \text{(f)} \end{aligned} \tag{17}$$

Here, $e = [1, \dots, 1]^T$, $s_l = \text{diag}(s_{l1}, s_{l2}, \dots, s_{lm})$, $s_h = \text{diag}(s_{h1}, s_{h2}, \dots, s_{hm})$.

These nonlinear equations are then solved by Newton's method [15].

The new approximation to the variables for the next iteration is determined by the following:

$$\begin{aligned} x^{k+1} &= x^k + \delta \cdot \Delta x & \gamma_g^{k+1} &= \gamma_g^k + \delta \cdot \Delta \gamma_g \\ \mu_l^{k+1} &= \mu_l^k + \delta \cdot \Delta \mu_l & s_l^{k+1} &= s_l^k + \delta \cdot \Delta s_l \\ \mu_h^{k+1} &= \mu_h^k + \delta \cdot \Delta \mu_h & s_h^{k+1} &= s_h^k + \delta \cdot \Delta s_h \end{aligned} \tag{18}$$

Here, scalar step size δ is chosen to preserve the nonnegativity conditions on slack variables s_l , s_h and dual variables μ_l , μ_h .

Instead of taking several Newton steps to converge to the optimal point of the subproblem with fixed μ , at each iteration μ is reduced until $\mu \rightarrow 0$ and Newton iteration gets the solution for Eq. (14).

6. Results and discussion

The model presented above is applied to a real case. A micro renewable hybrid power plant located in the CDER site, near Algiers, Algeria, is expected to supply a rural load composed of four households. The typical energy demand of each household is presented in Figure 3.

The work in [16] made an overview about generation costs of different electricity-generating technologies. In our case, the considered prices for the simulation are the following: 0.7\$/kWh for wind, PV, and battery charging; 0.9\$/kWh for battery discharging; 0\$/kWh for excess energy; and 2\$/kWh for undelivered energy. Characteristics of the diesel group are presented in the Table.

In order to show the effectiveness of the developed algorithm, several scenarios have been tested.

Table. Diesel generator parameters.

Maximal power (kW)	a (\$/(kW) ² h)	b (\$/kWh)	c (\$/h)
2	0.006	0.00657	0.5818

6.1. Optimal management in normal conditions

Figure 4 shows the dispatch of the different energy sources without management, following the principle of priority:

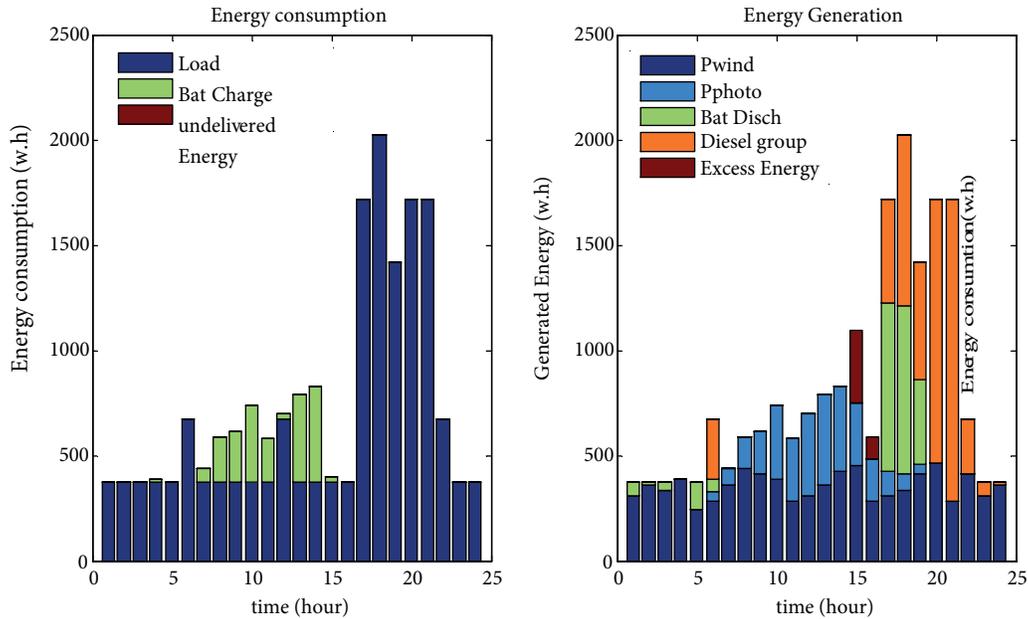


Figure 4. Energy source dispatch without management.

- Wind and photovoltaic.
- Battery discharge (if available)
- Diesel generator (if necessary).
- The surplus of energy is used for charging the battery.

The load is satisfied during all the simulation time (24 h). One can appreciate the battery charging at the intervals 2, 3, 4, 7, 8, 9, 10, 11, 13, 14, and 16 and the battery discharging at the intervals 6, 17, 18, 19, 20, and 21. The diesel group comes into action only at peak periods (at 0600 hours and from 1700 to 2100 hours). The daily energy generated cost of the plant is estimated at \$16.84.

The optimal dispatch using the developed algorithm is shown in Figure 5. Renewable sources are the first priority and second priority is given to the system management; this allows making an optimal decision between battery discharge and the diesel generator.

According to the cost function of the diesel generator (Figure 6):

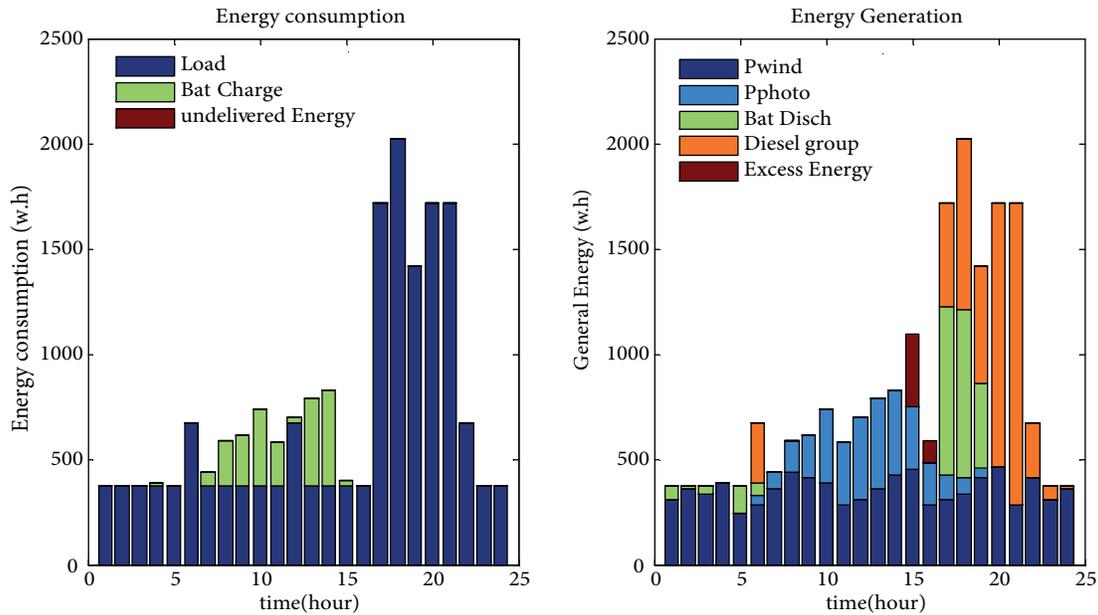


Figure 5. Optimal management in normal conditions.

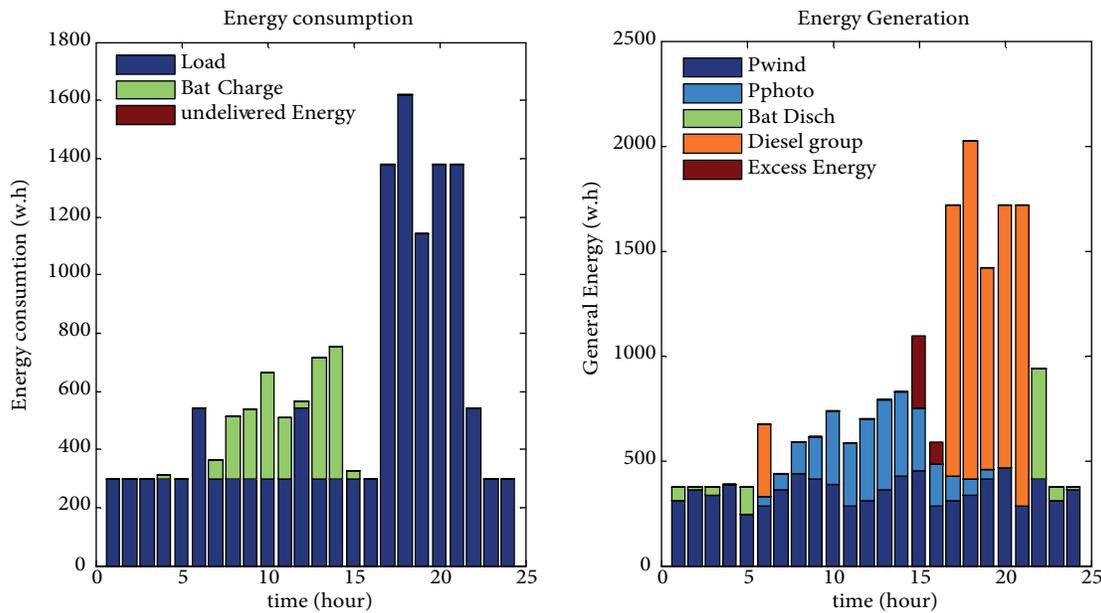


Figure 6. Cost function of the diesel generator.

- If energy cost is relatively high for low-energy demand, then the second priority is battery discharge (if available) and the third priority is the diesel generator.

- If energy cost is relatively low for high-energy demand, this makes the diesel generator the second priority and battery discharging the third priority.

The daily energy generated cost of the plant is estimated at \$14.12. Comparing to the dispatch without management, we notice significant cost savings estimated at \$2.72, which represents 16.15% per day.

6.2. Wind turbine failure

In this situation, to satisfy the load the diesel group comes into action for almost all of the simulation period (Figure 7). We note in this case a substantial increase in production cost estimated at \$19.60.

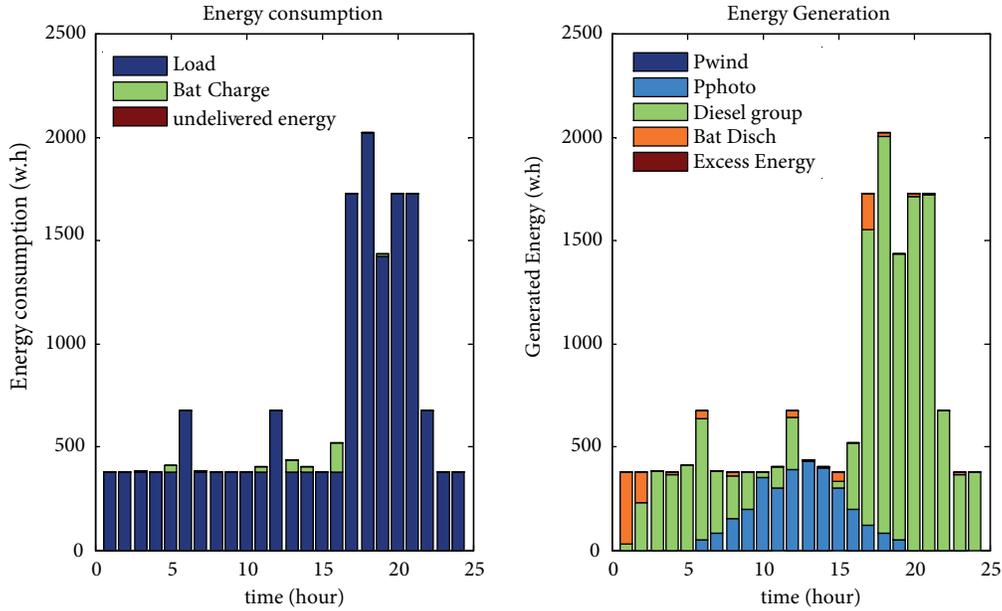


Figure 7. Optimal management while the wind turbine is out of order.

6.3. Diesel generator failure

Figure 8 represents the scenario where the diesel generator is out of order. Only renewable sources and battery are available to supply the load, which is not satisfied in this case. Lack of energy is represented by brown color in the left illustration. In this situation, we must either require households to reduce their consumption or resize the plant.

6.4. Minimum service

In order to ensure energy balance between the source and the load, the plant manager imposes a minimum service to households using smart meters. Secondary utility equipment must be cut off.

Figure 9 shows the optimal management of the system while the diesel generator is out of order. TVs and electric fans are cut off during the peak period and the equilibrium between source and load is ensured.

6.5. Households' evolution

In order to highlight the behavior of the power plant within the evolution of the number of households, we simulate the maximum number of households the plant can supply while ensuring energy balance. It is estimated herein at a maximum of 14 households (Figure 10); beyond these, we need to resize the plant.

7. Conclusion

In this paper, a scheduling problem has been formulated to identify the optimal operational management strategy for a sized renewable hybrid system. This operational strategy takes into account environmental changes, translated by the evolution of the number of customers (usually increasing), their consumption profiles, and

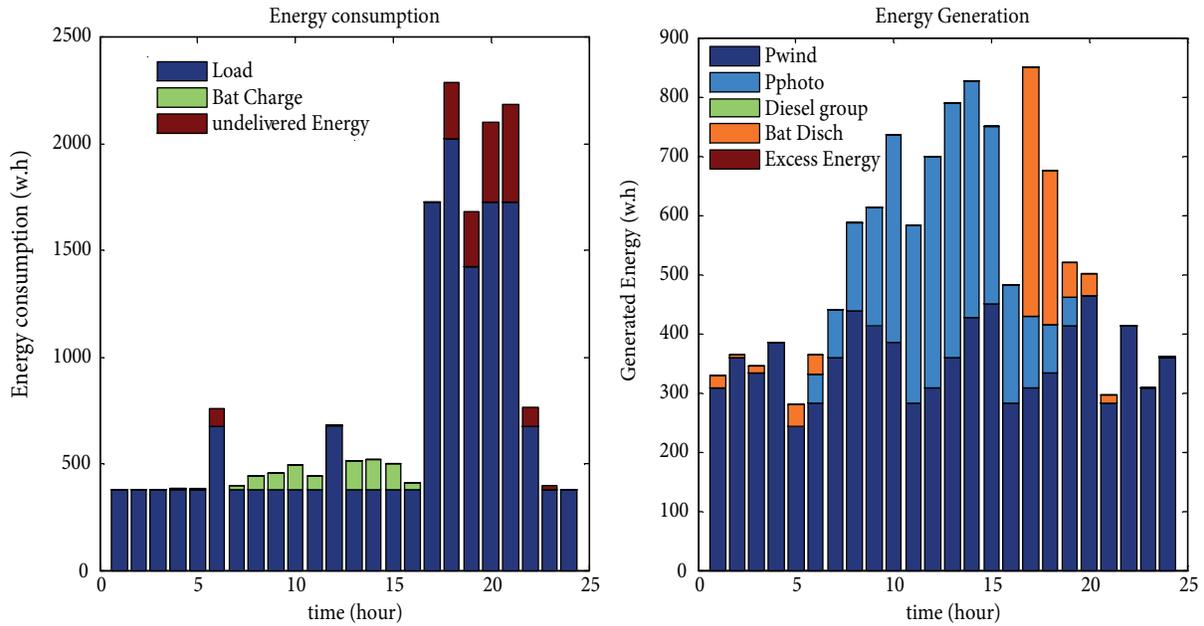


Figure 8. Optimal management while the diesel generator is out of order.

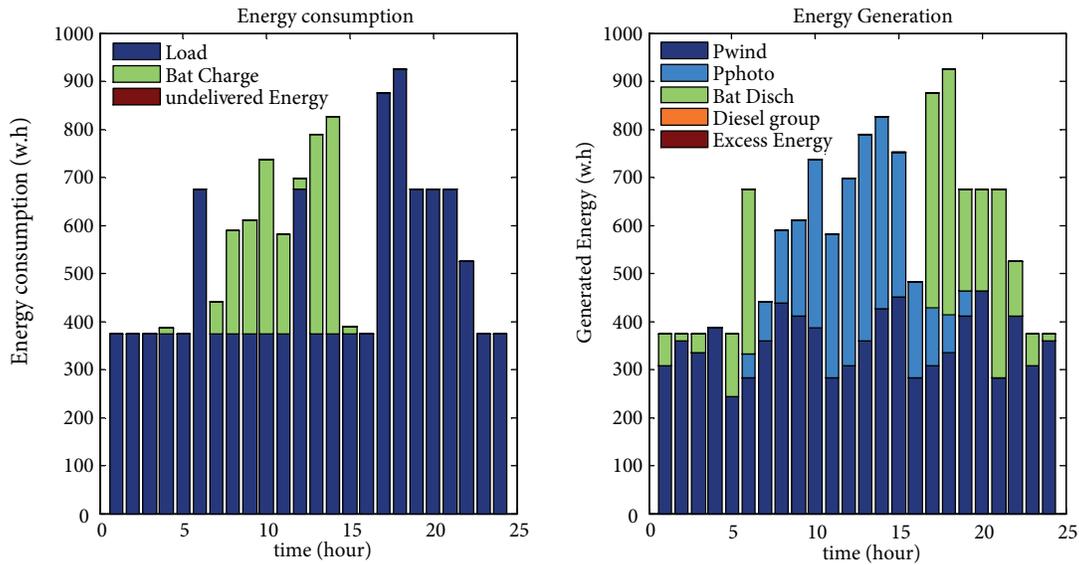


Figure 9. Optimal management while the diesel generator is out of order (minimum service).

eventual breakdown of a part of the plant. For optimal service quality, service continuity has been ensured while the generated energy cost has been minimized. The issue was modeled as a constrained quadratic problem and solved using the interior-point-convex algorithm implemented in MATLAB. As the initial conditions are well known in this kind of problem, it makes this technique easy to apply and not time-consuming. The approach presented in this work appears to be a suitable decision aid tool for the managers of autonomous power plants. However, due to the inevitable evolution of the plant environment, it would be interesting, as a prospect, to include in this work a technical and statistical study in order to define the right time to update the plant sizing.

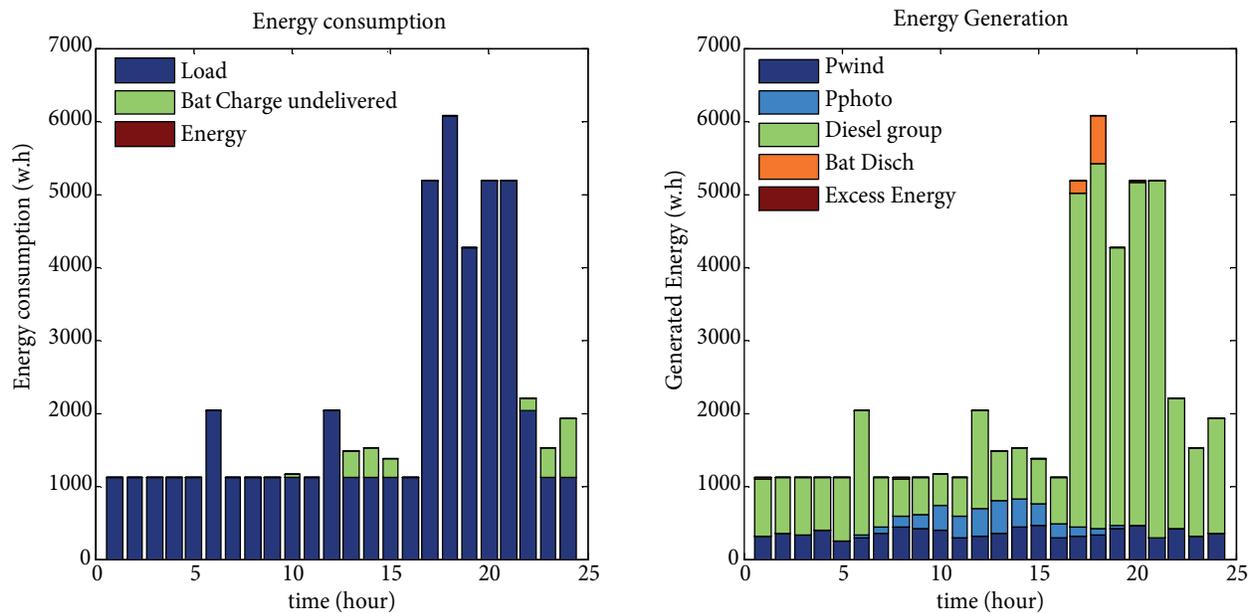


Figure 10. Optimal management of 14 households in normal conditions.

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