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Abstract— **This paper proposes an optimization-based decision support strategy to enhance the management of the distributed energy sources of an islanded microgrid. The solutions provided by the optimization algorithm are compared with the current strategy, already implemented in a real site microgrid on Lencois' island/Brazil. Significant economic and energy savings are achieved when the optimal management of the diesel generator is performed.**

Index Terms—**optimization, energy storage, renewables, microgrid**

I. Introduction

THE growing demand for energy poses serious environmental problems, such as the increase of greenhouse gas emissions and air pollution. This issue demands for reliable, stable and secure energy supplies. In this scenario, an important role can be played by the intelligent and efficient use of energy, including the use of Renewable Energy Sources (RES). However, the use of RES causes some implementation issues especially related to the uncertainty of electricity generation. Therefore, a lag of several hours may emerge between supply and demand, in which case the load should be balanced by Energy Storage Systems (ESS).

In light of the above, the energy management problem is considered to operate optimally the energy system that is currently working on Lencois' island, Brazil [1, 2]. The islanded microgrid is composed of a photovoltaic (PV) plant, three wind turbines (WT), a diesel generator and a battery bank as ESS. The diesel generator is needed as a reserve in case that neither the RES nor the ESS can provide energy to the load. Furthermore, it can be used as a backup unit in case of maintenance of the RES. This system has been working since 2008, and the main concern during this time period was related to the reliability of the energy supply. Efficiently operation was not a concern because all the efforts were to provide energy to the community 24 hours/day.

In steady state operation, the optimized operation becomes an important issue because the fossil fuel must be transported by boat to the island, rising its cost. Another obstacle are the environmental constraints of the island, which do not allow the storage of large amounts of fuel. This situation and the availability of only small boats for transportation affect the economy of scale of diesel, impacting the electric energy tariff of the island's consumers. Therefore, strategies to reduce the consumption of fossil fuel and maximize the exploitation of the capacity of existing renewable sources are necessary.

Previous research efforts have been made to optimally manage this kind of systems. In [3], a knowledge based expert system is proposed for the scheduling of a ESS installed in an islanded microgrid with diesel generator and RES. The strategy aims to minimize the use of the dump load associated with diesel generator operation. In [4], the management of a PV-diesel generator-battery hybrid islanded system is optimized comparing two operation modes of the diesel generator, namely the 'on-off' and the 'continuous' strategies. In [5], an optimal design methodology of islanded microgrids considering operational aspects is suggested, such that the total net economic benefit achieved during the system operational life is maximized.

However, there are few studies with microgrids with dominant hybrid renewable generation, which is the case of Lençois Island. In this case two types of generation uncertainty (wind and solar) and uncertainty in the demand should be considered, which depend on the geographic location and environmental conditions.

In this paper, a simplified optimization problem formulated as a Mixed Integer Linear Programming (MILP) is proposed. To assess the potential benefits that optimized energy management schedules may bring, the results are compared with those provided by the current implemented strategy. With respect to previous works, a sensitivity analysis based on different time-step intervals and time horizons is performed. Moreover, the robustness of the solution approach against changes in system parameters is assessed. To test the proposed optimization approach, results from simulation of the microgrid analyzed are considered.

II. Energy Management Strategy

In this section, the current heuristic strategy implemented on Lencois' island and the one based on optimization are explained and compared. The layout of the islanded microgrid and the main system features are highlighted in Fig. 1.

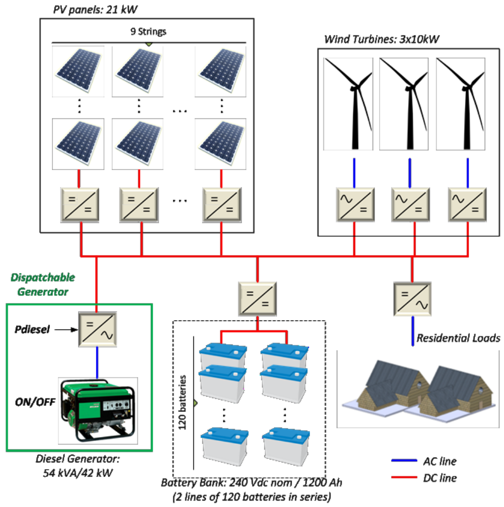


Fig. 1. Islanded microgrid: PV panels, Wind Turbines, Diesel Generator, Battery bank, Residential loads

A. Current Strategy

The system operates 24 h/day supplying the load. Each PV converter works based on a Maximum Power Point Tracking (MPPT) algorithm that charges the battery system and supplies the load. Whenever the State Of Charge (SOC) of the battery reaches 50%, the diesel generator is turned on for almost five hours, i.e. the average time required to fully charge the battery bank. During its operation, it supplies the load and charges the battery bank until the ESS reaches 100% of SOC.

Although the battery is charged to avoid damages, one problem is observed. Sometimes the diesel generator is turned on by the end of the day (for instance, between 11:00 pm and 2:00 am of the next day). At this time, the load demand is low and the diesel generator just charges the battery bank. During the next day, when there is production from RES, the battery bank is almost completely charged and the amount of energy that it can receive from RES is small, and the RES excess of generated energy is wasted. Basically, it means the ESS is charged mainly by the diesel generator and not by the RES.

Certainly, the current practice is based on greedy and conservative heuristic rules that can be improved by taking into account a systematic analysis of a convenient time window ahead, which is next addressed by formulating and solving the corresponding optimization problem.

B. Proposed Optimized Strategy

To overcome the limitations introduced by the current strategy, an optimization problem is formulated aimed at minimizing the objective function $f_1(x)$ as

$$\min f_1(x)[\$] = \sum_{t=1}^{T} \left(C_{DG}(t)\ [\$] + C_{Pexcess}(t)\ [\$]\right)\ \forall t \in \mathrm{T},$$

where $C_{DG}(t)$ corresponds to the operational cost of the diesel generator and $C_{Pexcess}(t)$ is the cost of not using the excess of energy from RES. This latter is included as a penalty function to ensure that the battery stores the surplus of energy generated by the RES and is expressed by,

$$C_{Pexcess}(t)\ [\$] = Cost_{pexcess}[\$/kWh] \cdot P_{excess}(t)[kW] \cdot \Delta t\ \ [h]$$

$$Cost_{pexcess}[\$/kWh] = cost[\$/l] \cdot p1_{DGcost}[l/kWh]$$

being $p1_{DGcost}$ a coefficient related to the diesel consumption. In turn, $C_{DG}(t)$ can be defined as

$$C_{DG}(t)\ [\$] = CVT_{DG}(t)\ [\$] + CFT_{DG}(t)\ [\$],$$

where $CVT_{DG}(t)$ is the cost related to the fuel consumption of the diesel generator and $CFT_{DG}(t)$ is the cost associated to the startup and shutdown of the diesel generator, which is a major concern for the manager. In general, $CVT_{DG}(t)$ for a diesel generator is expressed by

$$CVT_{DG}(t)[\$] = \sum_{t=1}^{T} \{cost[\$/l] \cdot g(t)[l/h]\} \cdot \Delta t\ \ [h].$$

Even though in most of the papers a quadratic or piecewise-linearization formulation is used as a cost function of the diesel generator [3, 6-8], from the datasheet of the manufacturer [9], $g(t)$ is a linear function. This is usually true for small diesel generators. In this way the problem can be formulated as a MILP problem

$$g(t)[l/h] = p1_{DGcost}\left[\frac{l}{kWh}\right] \cdot P_{DG}(t)[kW] + p2_{DGcost}\left[\frac{l}{h}\right] \cdot x_{DG}(t)\ \ \forall t \in \mathrm{T},$$

being $x_{DG}(t)$ a binary variable associated with the diesel generator status, $p2_{DGcost}$ another coefficient related to the diesel consumption and $P_{DG}(t)$ is the power of the diesel. The fixed cost associated to the startup and shutdown of diesel generator is expressed as

$$CFT_{DG}[\$] = \sum_{t=1}^{T} CF_{DG} \cdot x_{SU}(t)\ \ \ \forall t \in \mathrm{T},$$

where CF_{DG} is a constant cost and the binary variable $x_{SU}(t)$ is used to include the startup cost of the diesel generator by detecting the rising edge of $x_{DG}(t)$. It must fulfill the constraints

$$x_{SU}(t) \geq [x_{DG}(t) - x_{DG}(t-1)]\ \ \ \forall t \in \mathrm{T},$$
$$x_{SU}(t) \leq x_{DG}(t)\ \ \forall t \in \mathrm{T}.$$

Moreover, the energy balance of the overall system can be expressed as

$$P_{DG}(t) + \{P^{free}(t) - P_{excess}(t)\} + \left\{P_{bat}^{dis}(t) \cdot \eta_{dis} - \frac{P_{bat}^{ch}(t)}{\eta_{ch}}\right\} = P_{dem}(t)\ \forall t \in \mathrm{T},$$

where $P^{free}(t)$ is the energy from RES, $P_{bat}^{dis}(t)$ and $P_{bat}^{ch}(t)$ are the power of the battery during charging and discharging mode, η_{dis} and η_{ch} are the corresponding efficiencies and $P_{dem}(t)$ is the load demand. Besides, the relation of battery energy and SOC of the ESS can be defined as

$$SOC(t) = SOC(t-1) - \left[P_{bat}^{dis}(t) \cdot \eta'_{dis} - \frac{P_{bat}^{ch}(t)}{\eta'_{ch}}\right] \cdot \Delta t\ \ \ \forall t \in \mathrm{T}.$$

The following additional constraints are imposed, being $x_{bat}(t)$ a binary variable

$$P_{DG}^{min}(t) \cdot x_{DG}(t) \le P_{DG}(t) \le P_{DG}^{max}(t) \cdot x_{DG}(t) \; \forall t \in T,$$

$$P_{excess}(t) \ge 0 \quad \forall t \in T,$$

$$0 \le P_{bat}^{ch}(t) \le x_{bat}(t) \cdot P_{bat}^{ch,max} \quad \forall t \in T,$$
$$0 \le P_{bat}^{dis}(t) \le [1 - x_{bat}(t)] \cdot P_{bat}^{dis,max} \quad \forall t \in T,$$
$$SOC^{min} \le SOC(t) \le SOC^{max} \quad \forall t \in T,$$
$$E_{batnom} = C_{bat} V_{batnom},$$
$$\eta'_{dis} = \frac{\eta_{dis}}{E_{batnom}}, \quad \eta'_{ch} = \eta_{ch} E_{batnom}.$$

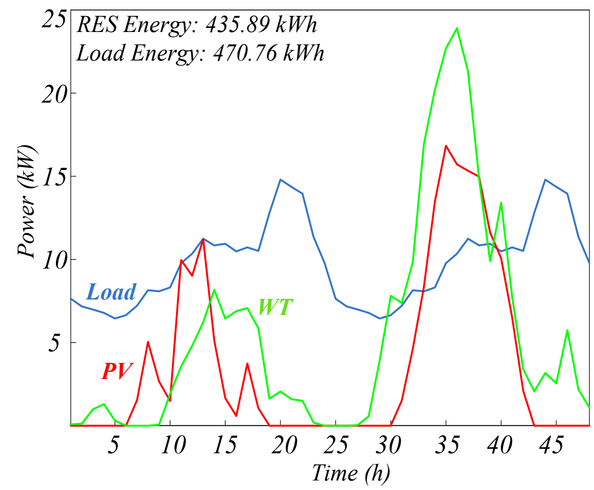
III. SCHEDULING RESULTS

To assess the benefits that the optimization approach may provide, a 48h time horizon is considered, for which historical data are used. Given this deterministic scenario, the decisions made following the present strategy are compared with the optimal ones in terms of diesel generator consumption, SOC, charging and discharging energy from the ESS, and excess of energy from RES. A time discretization approach is adopted and one-hour time intervals are used. The optimization strategy of the MILP problem is formulated in GAMS® using BONMIN as a solver. On the other hand, the present strategy is implemented in MATLAB®.

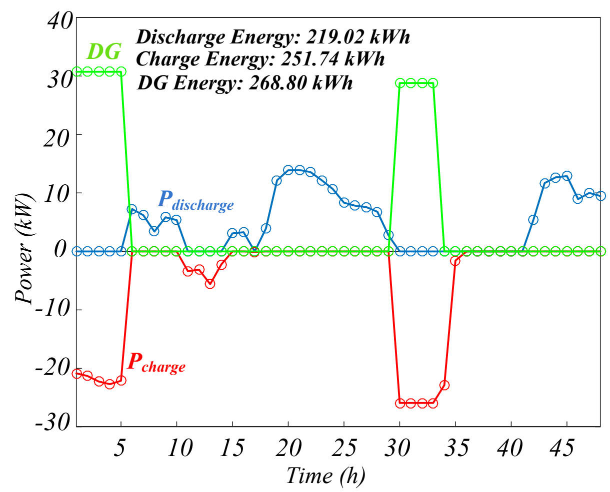
C. Comparative study and assessment of potential improvements

SOC profiles in Fig. 2(c_{NoOpt}) and Fig. 2($c_{WithOpt}$) clearly show the benefits of the optimization strategy. Without optimization, SOC increases at time 29h. This is due to the switching on of the diesel generator [see Fig. 2(b_{NoOpt})], as SOC reaches its minimum ($SOC^{min} = 50\%$). Thus, the production from RES increases in that period [see Fig. 2(a)]. As a consequence, at time 34h the battery bank is full ($SOC^{max} = 100\%$) and no more energy can be stored. This prevents a lot of available renewable energy to be seized within the following hours.

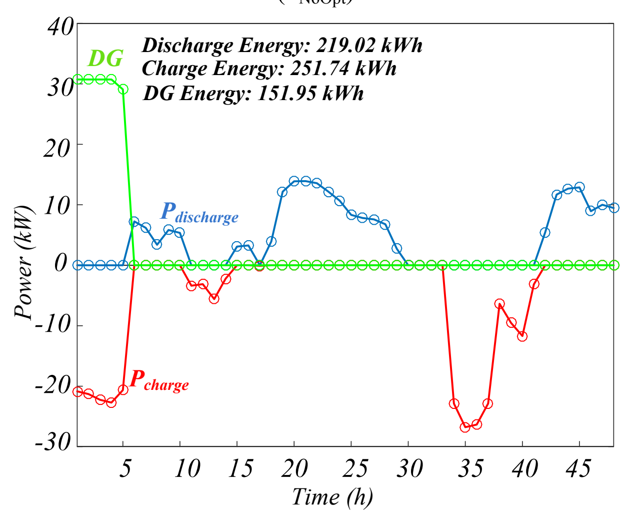
On the other hand, the optimization approach reveals that for this deterministic scenario the SOC could have been kept at its minimum from time 29h until time 33h, as shown in Fig. 2($c_{WithOpt}$). In this way, the battery bank is capable to store more renewable energy and there is no need to use the diesel generator [see Fig. 2($b_{WithOpt}$)]. These results reveal that significant cost reduction can be achieved (54.68 %, from \$ 113.25 to \$ 51.32), while exploitation of RES is increased by 48.45% from 280.72 kWh to 416.73 kWh.



(a)



(b_{NoOpt})



($b_{WithOpt}$)

reason, in the following simulations a time-step interval of one hour will be used.

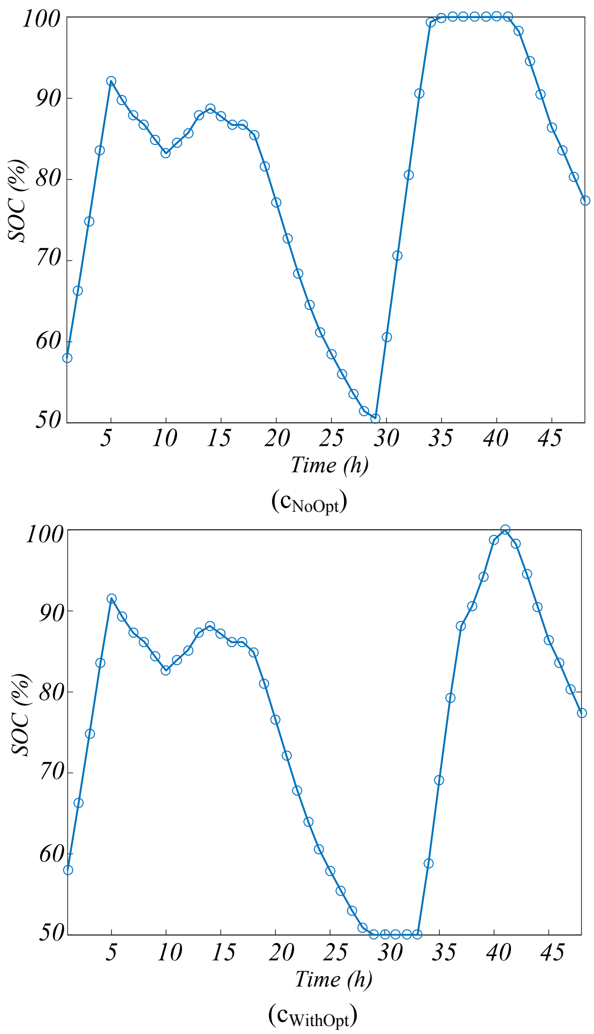


Fig. 2. Time horizon of 48 hours, time-step of 1h. Results for non-optimized strategy (NoOpt subscript) and from the optimization strategy (WithOpt subscript)

D. Sensitivity analysis

To assess to which extent the solutions provided via optimization are robust against parameters variation, firstly a sensitivity analysis based on a different time-step interval is performed. The same time horizon and energy profiles of Fig. 2(a) are considered for analysis, but a time-step interval of 15 minutes is set for the formulation of the optimization problem [see Fig. 3(a)]. The decisions to be taken are quite similar to the case corresponding to a one hour time-step interval. In particular, the decisions when the diesel generator has to be turned on [see Fig. 2(b$_{WithOpt}$) and Fig. 3(b)] are a little bit different: in Fig. 3(b) the diesel generator should be switched on also after around 70 minutes from the beginning of the time horizon. However, the energy globally required by the diesel generator, by the battery in charge and discharge mode are almost equivalent. In particular, the energy from the diesel generator differs by 0.05% respect to the results obtained with a time-step interval of one hour, respectively. Finally, the value of the objective function differs only by 1.29% compared to the one hour time-step interval formulation.

It can be stated that the formulation of the problem is robust enough against variations of the time-step interval. For this

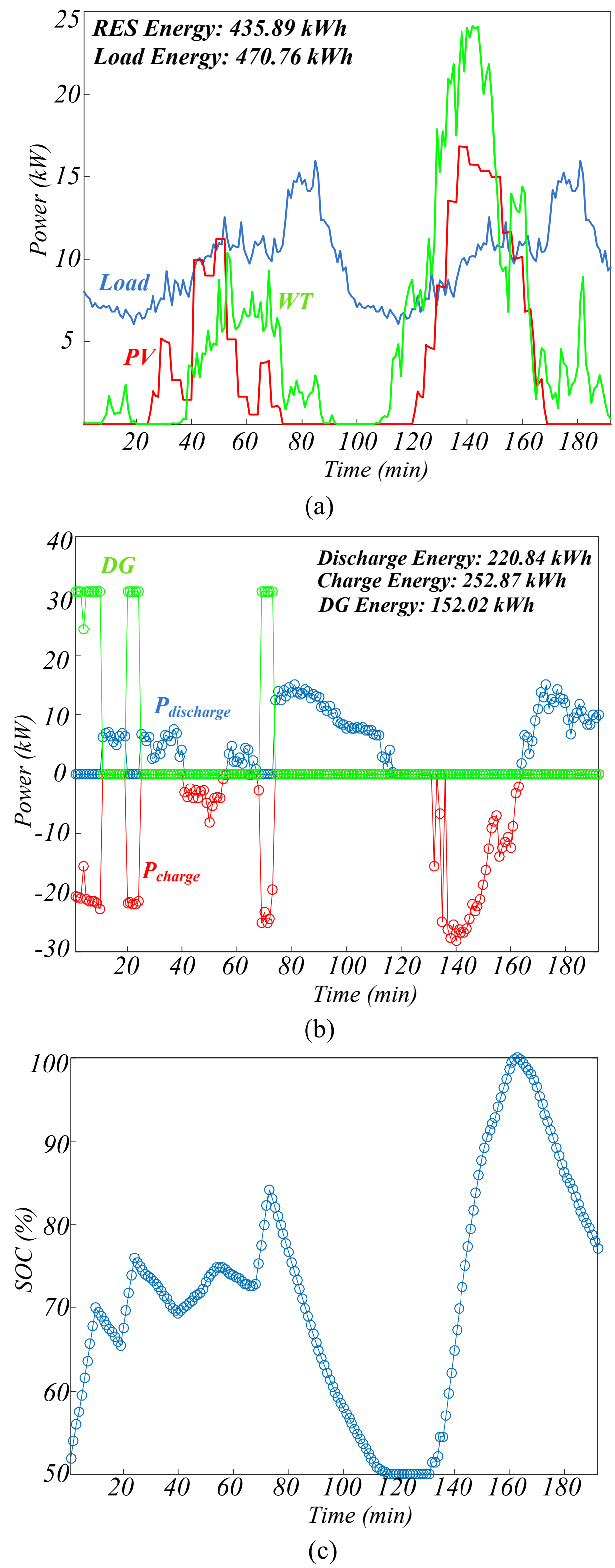
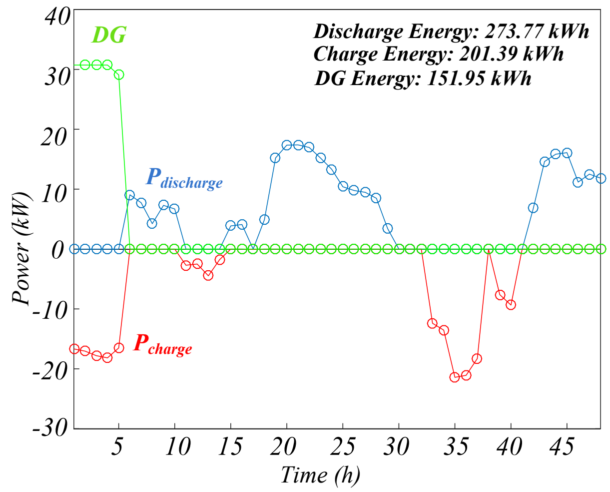
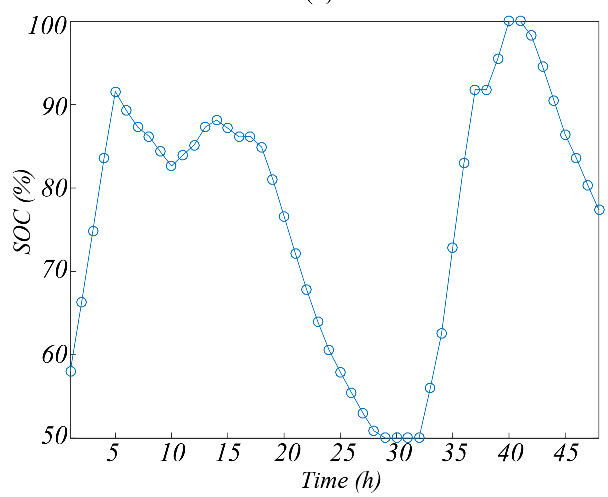


Fig. 3. Time horizon of 48 hours, time-step of 15 minutes. Results from the optimization strategy: (a) RES and load profiles; (b) DG, charge and discharge energy; (c) Battery SOC

A sensitivity analysis based on changes of system parameters is assessed. For this purpose, the efficiency of charge and discharge are lowered by 20%. The results are shown in Fig. 4. As expected, the results differ only in the values of the charge and discharge energy from the battery bank. The trend is almost the same for the case where no reduction of efficiency is expected (see Fig. 2).



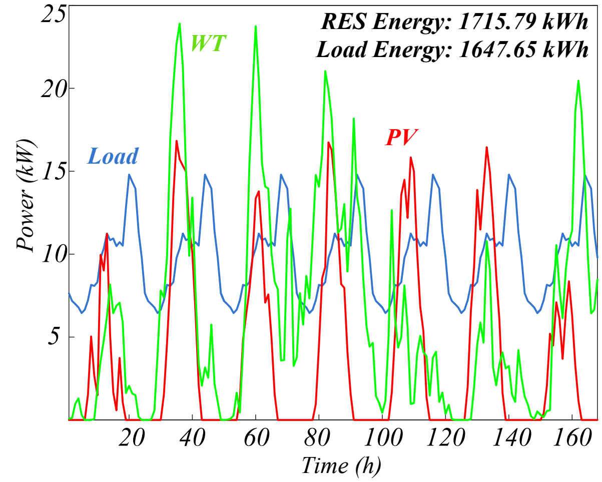
(a)



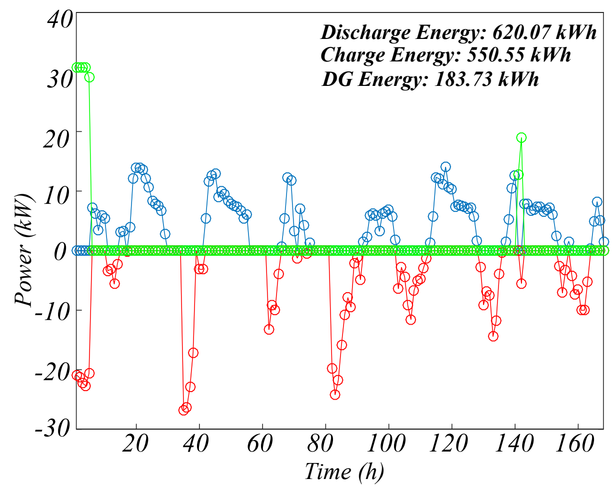
(b)

Fig. 4. Time horizon of 48 hours, time-step of 1 hour, $\eta_{charge} = 0.8\,\eta_{charge,nom}$; $\eta_{discharge} = 0.8\,\eta_{discharge,nom}$. Results from the optimization strategy: (a) DG, charge and discharge energy; (b) Battery SOC

Another sensitivity analysis is performed by considering a different time horizon, in particular of seven days. The subsequent five days to the two days previously considered are added in the time frame. The results are shown in Fig. 5. Compared to previous analysis [see Fig. 2($c_{WithOpt}$)], the battery pack is not fully charged (about SOC=90%) after almost 40h [see Fig. 5(c)]. The reason is to accommodate a higher amount of energy from RES in the subsequent days, since a longer time window is available. Apart from this small difference, the general trend in the first 48h is the same as previous analysis. These results demonstrate the robustness of the algorithm against different time horizons set for analysis.



(a)



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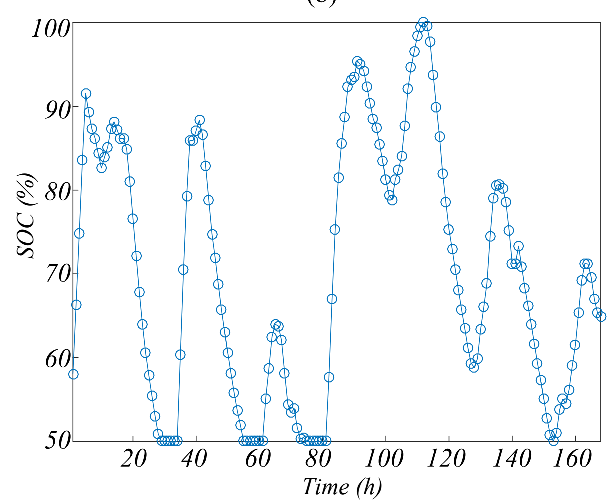


(c)

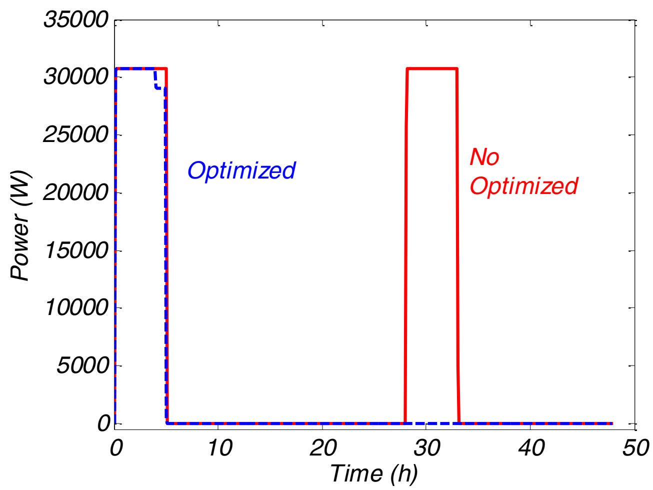
Fig. 5. Time horizon of 7 days, time-step of 1 hour. Results from the optimization strategy: (a) RES and load profiles; (b) DG, charge and discharge energy; (c) Battery SOC

IV. Simulation Results

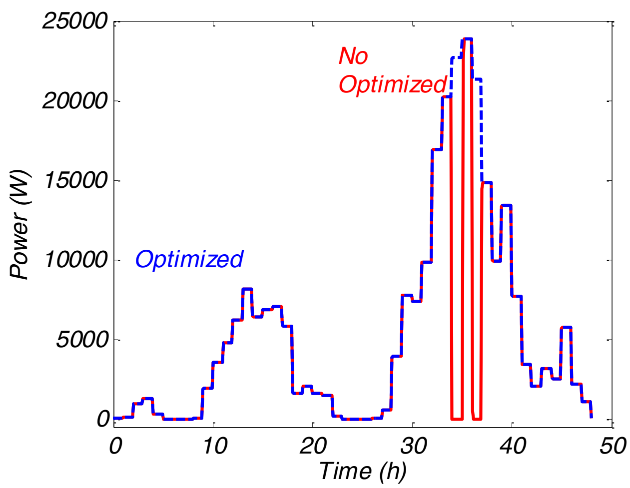
The results from scheduling are verified by a Simulink model of the microgrid. For this purpose, a low scale prototype of the islanded microgrid has been implemented that includes the dynamics of the power devices. As mechanism to limit the power in case of surplus of energy, the PV is switched off first and then the WTs. The used input data are the profiles presented in Fig. 2(a) as average values.

As shown in Fig. 6(a), the proposed optimization model allows minimizing the use of the diesel generator, in accordance with the results of Fig. 2($b_{WithOpt}$). For the selected days, the energy from WTs is totally exploited [see Fig. 6(b)]. On the other hand, the energy provided by PV [see Fig. 6(c)] is used in a more effective way than in the current strategy. This is because the optimization model can consider the predicted renewable energy generation and charge the battery accordingly. Hence, it is possible to store the surplus in the battery [see Fig. 6(d)] during high RES generation.

The comparison in the behavior of the battery with and without the scheduling of the diesel generator can be observed in Fig. 6(e). Most of the time, the two profiles are equal except for the timeframe highlighted by boxes B1 and B2. In B1 the diesel is still used to charge the battery in case of no optimal scheduling whereas, when optimization is used, the battery can be used before to supply the load. In B2, the optimized results show that the battery is charged more during this time, with the energy that comes from the RES.



(a)



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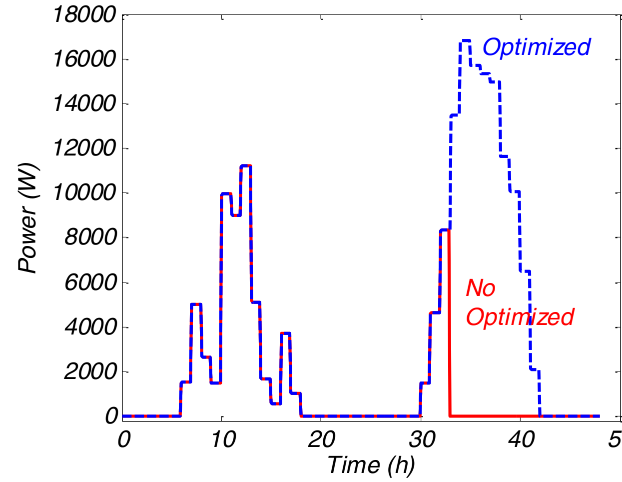

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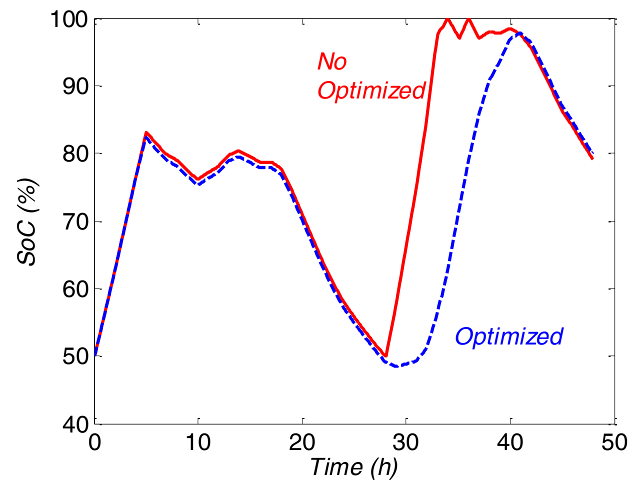

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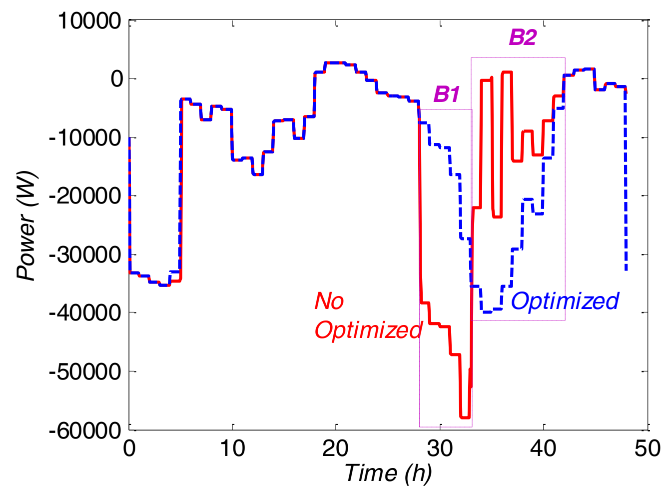

(e)

Fig. 6. Simulation results with and without using the scheduling of the diesel: (a) Diesel generator scheduling; (b) PV profiles; (c) WT profiles; (d) SOCs of the battery; (e) Profiles of the battery power.

V. Conclusions

The convenience of revising the energy management policy in an islanded microgrid has been verified. Compared to the current heuristic strategy, an optimization-based approach reveals remarkable saving opportunities, justifying its implementation. Despite the linearity of the optimization model, the behavior of the profiles is predictable, in particular for what concerns the load request. The sensitivity analysis shows that the optimization solver is robust enough against variations in the time step interval, timeframes and changes in system parameters.

To better quantify the savings provided by managing the system in a much more efficient way, further works aim to investigate different scenarios from the historical records, taking into account uncertainty both in generation and demand.

ACKNOWLEDGEMENT

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