ECONOMIC PERFORMANCE OPTIMIZATION OF A HYBRID PV- BESS POWER GENERATOR: A CASE STUDY LA REUNION ISLAND

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Abstract. *This paper proposes an economic performance optimization strategy for a PV plant coupled with a battery energy storage system (BESS). The case study of La Reunion Island, a non-interconnected zone (NIZ) with a high level of renewable energy sources (RES), is considered. This last decade, to reach the ambitious target of electricity autonomy by 2030 set by the local authorities, local and national plans have been launched to promote RES integration that led to a noticeable development of photovoltaic (PV) systems. To avoid a decrease of the grid reliability due to a large integration of intermittent energy sources into a non-interconnected grid, the authorities have introduced new regulatory rules for RES producers. The proposed optimization strategy relies on a these new regulatory rules and takes into account the energy market data, the amount of PV production subject to penalties for imbalance, the batteries and the PV technological characteristics together with a PV production forecast model. The effectiveness and relevance of the proposed strategy are assessed on experimental data collected on a real PV power plant. An economical analysis demonstrates that the proposed optimization strategy is able to fulfill the new regulatory rules requirements while increasing the economic performance of the system.*

1. Introduction

To date, reducing carbon emission has become a major concerned. Among possible options, increasing shares of renewable energy sources (RES) such as solar, wind or biomass resources appears as a promising solution for a cleaner power generation. High shares of RES may then become a critical aspect of future energy systems. In this context, small islands that mainly rely on imported fossil fuels for energy production are likely to be pioneers in the development of decarbonized electricity production **[1-2]**.

In this study, the case of La Reunion Island, a non-interconnected zone (NIZ), is considered. Even if the territory has a high level of RES, its electricity production remains strongly based on imported fuels. In this context, local authorities have set the ambitious objective of reaching electricity autonomy by 2030. This last decade, to reach this target, local and national plans have been launched to promote RES integration **[3-4]**. Thus, supported by incentive mechanisms such as tax exemptions, direct subsidies or feed-in tariffs, photovoltaic (PV) systems have experienced a rapid and noticeable development [**5**]. However, a large integration of intermittent sources into a non-interconnected grid raises critical technical issues due to the uncertainties of the energy production. The intermittency and unreliability of solar-generated power may reduce the network stability and lead to load shedding or to the interruption of electric service [**6**]. To avoid such situations, the authorities have set a limit of 30% of intermittent sources in the instantaneous electricity production and have introduced new regulatory rules for RES development. Henceforth, RES producers have to declare to the grid operator, a day in advance, the power profile that will be injected to the grid. Then, if the power plants do not meet the submitted schedule for injected power, they face financial penalties. In La Reunion Island, if mismatches between actual and scheduled power injection exceed a given tolerance, RES producers are charged with imbalance penalties. In order to address the problem related to the intermittency of solar-generated electricity while reducing the amount of PV production subject to penalties for imbalance, energy storage systems (ESSs) appears as one of the most relevant option. Recently, several works related to the applicability, advantages and disadvantages of various ESS technologies for RES integration have been reported **[7]**. As regards PV power plants coupling with ESS, several works dealing with technical issues and economic feasibility have been conducted **[8-11]**. However, from a regulatory point of view (incentive schemes and economic feasibility), nearly all works reported in the literature focus on the determination of the optimal sizing of the ESS **[12-15]**.

In the case of La Reunion, and according to our best knowledge, none work has been conducted to optimize the economical performance of existing hybrid photovoltaic-battery energy storage system (BESS) power generators, based on the latest regulatory rules. In this paper, an economical optimization of a hybrid PV-BESS power generator is developed. The proposed methodology relies on a *metaheuristic* optimization algorithm taking into account the energy market data, the amount of PV-generated energy subject to penalties for imbalance, the PV and the batteries technological characteristics together with a PV production forecast model. To assess the effectiveness and relevance of the proposed strategy, the economic analyses are performed on data measured on a real power plant. Indeed, a one-year experimental data, collected from August 2013 to August 2014 on a 57 kWp PV farm coupled with a 78.5kWh BESS, are considered.

The rest of this paper is organized as follows. The regulatory rules applied in La Reunion are presented in Section 2. Section 3 is dedicated to model design. In this section the PV production forecast model and the energy storage model are detailed. The performance of the proposed optimization strategy in terms of economical efficiency improvement is demonstrated in Section 4.

Table 1: Nomenclature.

Variable	Description [unity]
P_{bid}	Scheduled profile to be injected to the grid [kW]
P_{inj}	Power injected to the grid [kW]
P_{PV_m}	Measured PV power [kW]
P_{PV_f}	Forecasted PV power [kW]
P_{PV_peak}	Installed PV power capacity [kW_p]
P_{sto}	Storage power [kW] (*>0* charge, *<0* discharge)
P_{sto_AC}	Storage power exchanged with the AC bus
$-P_d$	Maximal power in discharge [kW]
P_c	Maximal power in charge [kW]
P_I	Imbalance power [kW]
E_{sto_peak}	Amount of energy dedicated to evening peak [kWh]
$E_{PV\_f\_total}$	Estimated total energy produced by PV plant [kWh]
α_{peak}	Parameter to be estimated
$\beta_{forecast}$	Parameter to be estimated
C_{max}	Maximum usable storage capacity [kWh]
SOC_{min}	Min. energy storage level [%C_{max}]
SOC_{max}	Max. energy storage level [%C_{max}]
η_c	Efficiency of storage in charge
η_d	Efficiency of storage in discharge
C_s	Electricity selling price
C_b	Electricity buying price
DFR	Daily fault rate
τ_{fault}	Cumulated time of faulty condition [minute]

2. Regulatory rules

In NIZ such as La Reunion, the large integration of intermittent sources raises critical technical issues related to the reliability of power supply. The reliability of an electrical grid can be defined by its ability to supply the aggregate electrical demand and energy requirements of the customers at all times, while withstanding sudden disturbances such as unanticipated loss of system elements (e.g. load or production fluctuations) **[16-18]**. Currently the sustainability of power supply in La Reunion is already lower than in Metropolitan France, with an average power outage duration estimated at 4 h/year/consumer *vs* 73 min **[5]**. In this context, and considering the rapid and important growth of PV systems in La Reunion the last decade, the authorities have recently decided to set up new regulatory rules to ensure the reliability of the power supply. Henceforth, producers have to declare a one minute based profile that represents the day-ahead forecasted power to be injected by their plants. If the mismatches between the actual injected power and the announced power exceed the admitted tolerance, financial penalties are applied. According to this regulatory framework, energy imbalance is calculated with minutely resolution, and the tolerance band is taken equal to ± 5% of the installed PV power capacity (P_{PV_peak}).

The electricity tariff system relies on peak and off-peak hours. During peak hours, 7PM to 9PM, the electricity feed-in tariff is more attractive. However, during this time period, producers have to guarantee a constant power injection to the grid comprise between 20 % and 70 % of P_{PV_peak}. The current electricity tariff system applied to PV power producers in La Reunion, including peak and off-peak feed-in tariffs, is summarized in **Table 2**.

Table 2: Summary of tariff system in La Reunion.

	Peak hours (7PM to 9PM) [€ ct/kWh]	Off-peak hours [€ ct/kWh]
Selling price (C_s)	60	40
Buying price (C_b)	40	40

Note that producers have the possibility to buy electricity from the grid. In some very specific cases, it could be interesting to buy electricity from the grid during off-peak, store the energy in an ESS, and sell it back during peak hours.

The producer's revenue is calculated each minute using the following expression:

$$revenue = P_{inj}\,C_S/60 - P_{out}\,C_b/60 - penalties \quad (1)$$

where P_{inj} denotes the power injected to the grid and P_{out} the power extracted from the grid. The financial penalties are calculated as follows:

if $P_{bid} - 0.05\,P_{PV\_peak} < P_{inj} < P_{bid} + 0.05\,P_{PV\_peak}$ ***then***

$penalties = 0$

elseif $P_{inj} > P_{bid} + 0.05\,P_{PV\_peak}$ ***then***

$penalties = P_{inj}\,C_S/60$

else

$$penalties = \frac{C_s}{60}\left[P_{inj}\frac{P_{inj}}{P_{PV_{peak}}} - \left(0.1 + \frac{2P_{bid}}{P_{PV_{peak}}}\right)P_{inj} + \left(P_{bid} - 0.05P_{PV\_peak}\right)\left(0.015 - \frac{P_{bid}}{P_{PV_{peak}}}\right)\right]$$

where P_{bid} denotes the day-ahead schedule power profile to be injected to the grid.

Every time P_{inj} is outside the tolerance band, the system is said to be in faulty condition and financial penalties are applied.

In this work, the economic effectiveness of the system is assessed using two criteria, which are the revenue and the daily fault rate (DFR). This last criterion defines the ratio of time where the system is in faulty condition each day:

$$DFR = \tau_{fault}/1440$$

With 1440 minutes per day, τ_{fault} represents the cumulated time of fault condition in minute.

To fulfill the requirements of the new regulatory rule, PV power producers have to announce a day in advance the power profile to be injected to the grid, which requires a PV production forecast model. Besides, regardless of the accuracy of the PV production forecast model, financial penalties due to imbalance are unavoidable. Therefore, to reduce financial penalties and above all take advantage of peak hours feed-in tariff, the use of ESS appears to be a relevant option.

3. Model design

PV production forecast model

In the literature, a wide variety of parametric and non-parametric forecast models have been reported **[19]**. Parametric models require a wide set of information about the PV power plant technology and its installation configuration. Non-parametric models are generally based on weather forecast models **[20]**. These limitations make the reliability and the suitability for "on field" uses of parametric and non-parametric forecast models questionable.

In this study, regarding practical purposes, the widely used persistence model is chosen to forecast the PV output power at a minute basis. This is a simple model based on the assumption that the PV production of today is the same as yesterday **[21]**:

$$P_{PV\_f}(t) = P_{PV\_m}(t - 1440) \tag{2}$$

where P_{PV_f} and P_{PV_m} denotes respectively the measured and forecast PV output power at time t.

Even if this method does not take into account the intra-day variability of solar irradiance, it represents with a good accuracy the periodicity and seasonality of weather conditions (day/night and summer/winter cycles) **[13]**. Besides, as a low-tech approach compared with irradiance forecast based strategies, it has the merit of avoiding additional costs, which cannot be underestimated for small cases applications. Obviously, the accuracy of the PV production forecast could be improved using more sophisticated models but at the price of increasing complexity and computational cost.

Energy storage model

Regarding optimization purposes and according to the considered time scale (minutes in this study), a simplified static model is proposed. This model relies on the static characteristics of the battery (*Cf.* table 3) and neglects the transient dynamics of the process. In the sequel, powers are considered negative (respectively positive) during the discharge (respectively charge) phase. In this context, the battery state of charge (SOC) at time t is computed by:

$$SOC(t) = SOC(t - \Delta t) + P_{sto}(t)\Delta t / C_{max} \tag{3}$$

Subjected to constraints on power and capacity:

$$\begin{cases} P_d \leq P_{sto}(t) \leq P_c \\ SOC_{min} \leq SOC(t) \leq SOC_{max} \end{cases} \tag{4}$$

where $P_{sto}(t)$ is the storage power at time t. $P_d < 0$, $-P_d$ represents the maximum battery discharging power, and $P_c > 0$ the maximum battery charging power. SOC_{min} and SOC_{max} are the minimum and maximum battery state of charge, respectively. C_{max} denotes the maximum usable storage capacity of the ESS. Note that the battery aging and self-discharge rate, which obviously affect C_{max}, has not been considered. Besides, powers are considered constant during the time interval $[t;\ t + \Delta t]$. In this work, Δt is equal to one minute.

The PV, battery, grid, and loads are all connected to an AC bus. Since the battery is operated on DC, an AC-to-DC (respectively DC-to-AC) converter is necessary when charging (respectively discharging) the battery. Therefore, considering the storage charge and discharge efficiencies (η_c and η_d respectively), the storage power exchanged with the AC bus $P_{sto\_AC}(t)$ is expressed as follows:

$$\begin{cases} P_{sto\_AC}(t) = P_{sto}(t)\,\eta_d & \text{if } P_{sto}(t) < 0 \text{ (discharge)} \\ P_{sto_{AC}}(t) = P_{sto}(t)/\eta_c & \text{if } P_{sto}(t) \geq 0 \text{ (charge)} \end{cases} \tag{5}$$

Table 3: Storage system parameter values.

Variable	Description [unity]	Value
C_{max}	Maximum storage capacity [kWh]	78.5
SOC_{min}	Min. energy storage level [% C_{max}]	20
SOC_{max}	Max. energy storage level [% C_{max}]	99
η_c	Efficiency of storage in charge	0.9
η_d	Efficiency of storage in discharge	0.9
$-P_d$	Maximal power in discharge [kW]	36.1
P_c	Maximal power in charge [kW]	17.2
DOD_{max}	Maximal depth of discharge [%]	80

4. Economic performance optimization

In this work, a minute dispatch strategy for a 57 kWp PV farm with 78.5 kWh BESS is implemented and an economical optimization of the dispatch strategy is proposed. BESS has two main applications: first, compensate PV production forecast errors during off-peak and thus reduce financial penalty due to imbalance. Second, inject power to the grid during peak hours and thus take advantage of the attractive feed-in tariff. In this context, two parameters are introduced. The first one, denoted α_{peak}, is related to the amount of energy dedicated to the evening peak hours (E_{sto_peak}), which have to be stored in the BESS meanwhile, and is written as a fraction of the estimated total energy produced by the PV plant ($E_{PV\_f\_total}$):

$$E_{sto\_peak} = \alpha_{peak}\, E_{PV\_f\_total} \qquad (6)$$

Here $E_{PV\_f\_total} = \int_0^{1440} P_{PV\_f}\,dt$. The second one, denoted $\beta_{forecast}$, represents the fraction of the storage capacity that is dedicated to compensate power imbalance ($C_{foreacast}$) due to forecast errors:

$$C_{foreacast} = \beta_{forecast}\, C_{max} \qquad (7)$$

To assess the effectiveness and relevance of the proposed strategy, the economic analyses are performed on a one-year experimental data, collected from August 2013 to August 2014 at La Reunion on a real PV power plant. Due to its high convergence rate to the true global minimum and its perfect suitability to practical engineering optimization problems, the recently developed Modified Cuckoo Search algorithm proposed by **[22]** is used as optimization algorithm.

PV/BESS control rules

The power injected to the grid is defined as the sum of the PV output power and the storage power exchanged with the AC bus:

$$P_{inj} = P_{PV\_m} + P_{sto\_AC} \qquad (8)$$

The BESS is used to adjust the PV power plant P_{PV_m} to maintain, as much as possible, the difference between the day-ahead announcement P_{bid} and the actual power injected P_{inj} to the grid within the tolerance band. If P_{PV_m} is above (respectively below) the tolerance limit, the BESS can be used, when it is possible, to store (respectively deliver) the imbalance power P_I. Depending on whether the measured output PV is within, below or above the tolerance band, P_I is defined as follows:

$$\begin{cases} P_I = 0 & \text{within} \\ P_I = P_{PV\_m} - \left(P_{bid} + 0.05\, P_{PV_{Peak}}\right) & \text{above (charge)} \\ P_I = P_{PV\_m} - \left(P_{bid} - 0.05\, P_{PV_{Peak}}\right) & \text{below (discharge)} \end{cases} \qquad (9)$$

Every time $P_I \neq 0$ financial penalties for imbalance are applied. Therefore, the storage charge/discharge process must be suitably controlled in order to reduce the DFR and thereby the amount of financial penalties, while ensuring that there is enough energy stored in the BESS for the evening peak. In this aim, a tolerance band control strategy is proposed and a specific control rules is designed for each zone: above, within and below the band.

<u>Above the upper limit</u>

When P_{PV_m} is above the tolerance band, the BESS is used to compensate the imbalance power and store the excess of energy whenever possible. Indeed, the imbalance power cannot always be compensated. Several conditions related to operational and technical limits of the BESS have to be verified (i.e state of charge, charge/discharge rate limits). In this case, the storage power is computed as follows:

$$P_{sto\_AC} = min\left(P_c/\eta_c, P_I, P_{sto\_MAX}/\eta_c\right) \qquad (10)$$

where $P_{sto\_MAX} = \left(SOC_{max} - SOC(t)\right)C_{max}/\Delta t$

<u>Below the lower limit</u>

When P_{PV_m} is below the tolerance band, the imbalance power due to forecast error can be compensated using the energy stored in the BESS. However, this energy has to be manipulated very wisely in order to ensure that enough energy remains to guarantee peak hours. The storage power is calculated according to operational and technical limits of the BESS and subjected to constraints on E_{sto_peak} and $C_{foreacast}$:

$$P_{sto\_AC} = max\left(P_d\eta_d, P_I, -P_{sto\_MAX}\eta_d\right)\ if\ SOC(t) > E_{sto_{peak}}/C_{max}$$
$$otherwise\ P_{sto\_AC} = 0 \qquad (11)$$

where
$$P_{sto\_MAX} = min\left(\left(SOC(t) - E_{sto\_peak}/C_{max}\right)C_{max}/\Delta t,\ C_{foreacast}/\Delta t\right)$$

<u>Within the tolerance band</u>

When P_{PV_m} is within the tolerance band, the power imbalance is equal to zero and there is not need to absorb/inject power from/to the grid through the BESS:

$$P_{sto\_AC} = 0 \qquad (12)$$

Economic performance improvement

The economical performance improvement relies on the estimation of two parameters α_{peak} and $\beta_{forecast}$. The effects of these parameters on the annual revenue and the average annual DRF are illustrated on **Fig. 1 and 2**.

As expected, while $\beta_{forecast}$ is increasing the DRF is decreasing. Indeed, $\beta_{forecast}$ is straightforwardly linked to the fraction of the storage capacity dedicated to compensate power imbalance due to forecast errors. However, it is important to highlight that decreasing the DRF and so the financial penalties do not necessary means increasing the revenue. In fact, while $C_{foreacast}$ becomes closer to C_{max}, the amount of energy that can be stored in the BESS for the evening peak hours decreases. Since peak hours feed-in tariff is more attractive than off-peak one, it could be more interesting to sell more energy during peak hours even if that means paying more penalties during off-peak due to forecast error.

As illustrated on **Fig. 2**, while α_{peak} is increasing the DRF is increasing, whereas the revenue increasing to a maximum before decreasing. Which seems indicate that, for a fixed value of $\beta_{forecast}$, there is an optimal amount of energy to store in the BESS for the evening peak hours.

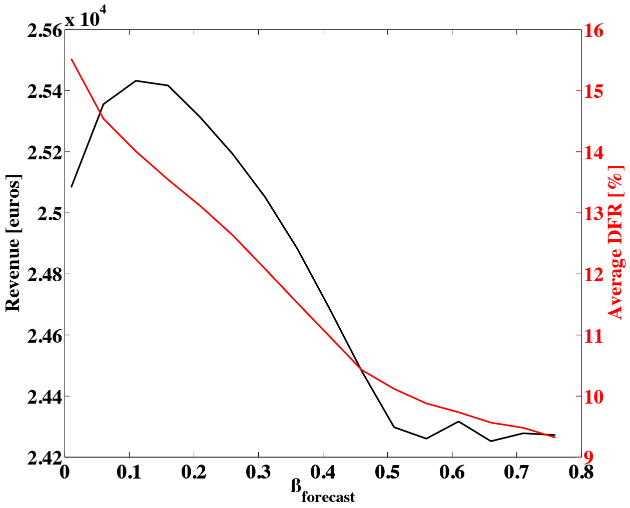

Fig. 1: Effects of $\beta_{forecast}$ on the revenue and the DRF (with $\alpha_{peak} = 0.3$ and calculated over one year)

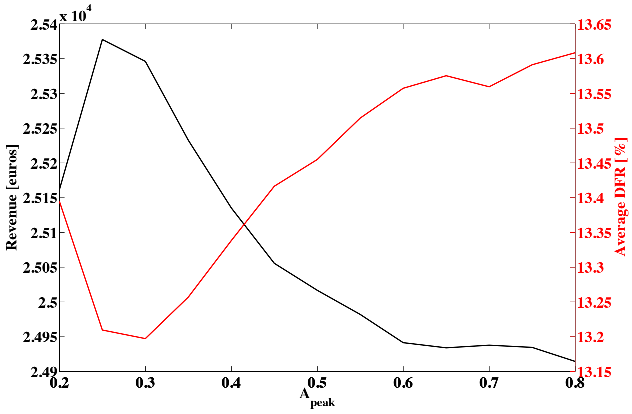

Fig. 2: Effects of α_{peak} on the revenue and the DRF (with $\beta_{forecast} = 0.2$ and calculated over one year)

Annual optimization

In a first attempt, the economic performance improvement strategy consists on finding the optimal values of α_{peak} and $\beta_{forecast}$ that maximizes the annual revenue. The optimization goal is to find the optimal set of parameter $\hat{p} = [\alpha_{peak}\ \beta_{forecast}]^T$ that maximizes the cost function *J*:

$$\hat{p} = \underset{p}{argmax}(J) \qquad (13)$$

with $J = \sum_{j=1}^{365}\sum_{i=1}^{1440}(P_{in}^{i,j}C_s/60 - P_{out}^{i,j}C_b/60 - Penalties^{i,j})$ and subjected to $p \in [p_{min}, p_{max}]$; $p_{min} = [0\ 0]^T$; $p_{max} = [1\ 0.8]^T$.

The optimization procedure, performed on experimental data collected from August 31st 2013 to September 1st 2014, leads to the optimal set of parameter $\hat{p} = [0.2978\ 0.1387\ ]^T$, which results to an annual revenue of 25 449.20 euros and an average DRF of 13.12%. The revenue and the DRF for each day are presented in **Fig. 3.**

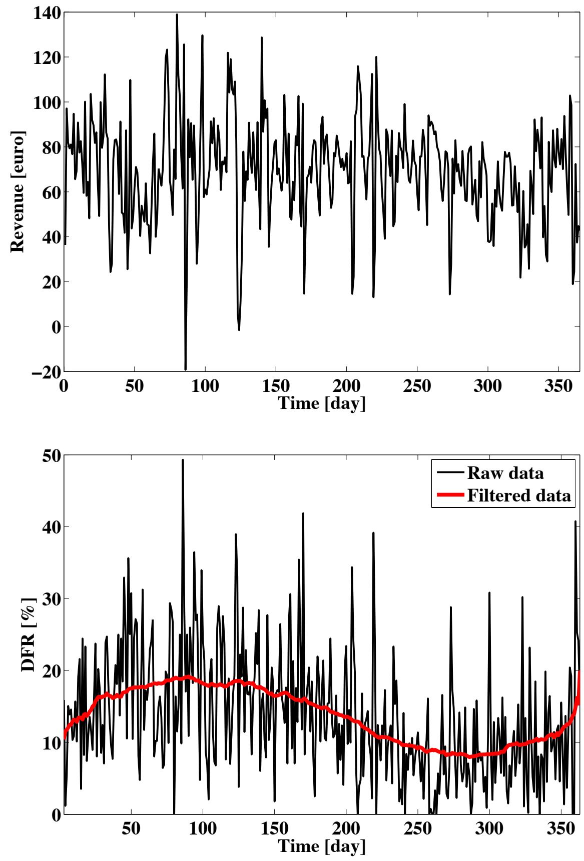

Fig. 3: Daily revenue and DRF obtain over one year

It can be noticed that the DFR seems to contain a periodic component. The analysis of the DFR in the frequency domain reveals that the frequency component with the higher magnitude is located at 0.002732 day^{-1}, which corresponds to a periodicity of 366 days. Moreover, a thorough study of the DRF reveals a strong and significant correlation between DRF and the forecast error, with a Pearson's correlation coefficient of 82% (*p-value* < 0.0001).

The analysis of the forecast error reveals the same periodicity of 366 days, which means that the forecast error is linked to the season. Indeed, as illustrated on **Fig. 4**, the forecast error is higher in summer than in winter.

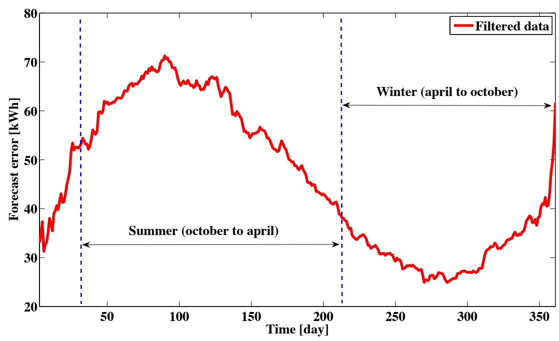

Fig. 4: Forecast error

This can be mainly explained by the fact that the forecast model does not take into account the intra-day variability of solar irradiance and that in La Reunion Island the intra-day variability is higher in summer. In this context, when the intra-day variability increases the error modeling increases too, which leads to an increase of the DFR. In other worlds, the seasonality of the solar irradiance variability introduces a seasonal component into the forecast error that is transmitted to the DFR.

The analysis of the total energy produced by the PV plant each day ($E_{PV\_f\_total}$) reveals a seasonal component that is due to the yearly solar irradiance variability (*Cf.* Fig. 5). The amount of energy dedicated to the peak hours (E_{sto_peak}), which could have a strong influence on the revenue, is taken as a fraction of $E_{PV\_f\_total}$ using α_{peak}. In this context, the seasonal component contained into $E_{PV\_f\_total}$ is transmitted to E_{sto_peak}. A thorough study of intra-day and yearly irradiance variability in La Reunion can be consulted in [**23**].

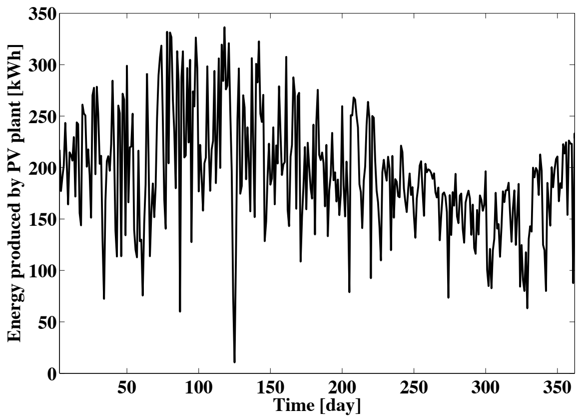

Fig. 5: Energy produced by the PV plant

Regarding the seasonality of the solar irradiance, and since $\beta_{forecast}$ and α_{peak} respectively influence the DRF and the amount of energy dedicated to the peak hours, it is likely that a seasonal-based or even a daily-based optimization of these parameters could increase the revenue.

6. Conclusions and prospects

In this work, a minute dispatch strategy for a 57 kWp PV farm with 78.5 kWh BESS has been simulated, and an economical optimization of the dispatch strategy has been developed. This strategy has been designed to fulfill the requirements of the new regulatory rules set in La Reunion while optimizing the economic performance of the system. The BESS is used during off-peak to compensate PV production forecast error and during peak hours to inject power to the grid. Therefore, two parameters have been introduced. The first one is related to amount of energy to store for the evening peak hours whereas the second one represents the fraction of the storage capacity that is dedicated to compensate power imbalance due to forecast errors. The optimization goal is to find the optimal value of these parameters that maximizing the revenue while taking into account the new regulatory rules constraints. The proposed optimization strategy takes into account the energy market data, the amount of PV production subject to penalties for imbalance, the batteries and the PV technological characteristics together with a PV production forecast model. The effectiveness and relevance of the proposed strategy have been assessed on experimental data collected on a real PV power plant. An economical analysis demonstrated that the proposed optimization strategy has been able to fulfill the new regulatory rules requirements while increasing the economic performance of the system.

Due to the seasonal behavior of solar radiation, it is likely that economical performance can be further increased using a seasonal-based optimization approach. Additional works are currently in progress to study if the revenue can be increased by taking into account the seasonal component contained in the forecast error and the total energy produced by the PV plant.

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References

[1] Weisser D. On the economics of electricity consumption in small island developing states: a role for renewable energy technologies? Energy Policy 2004;32(1):127–40. http://dx.doi.org/10.1016/S0301-4215(03)00047-8.

[2] Guerassimoff G, Maïzi N, Mastère. OSE. Îles et Énergie: un paysage de contrastes. Les Presses-MINES ParisTech; 2008 [in french].

[3] ARER. PETREL - île de la Réunion. Plan économique de Transition et de Relance *via* des énergies 100 % Locales île de la Réunion. *Technical Report, ARER*; 2009 [in french].

[4] Praene JP, David M, Sinama F, Morau D, Marc O. Renewable energy: progressing towards a net zero energy island, the case of Reunion Island. *Renew Sustain Energy Rev 2012*;16(1):426–42. http://dx.doi.org/10.1016/j.rser.2011.08.007.

[5] Drouineau, M., Assoumou, E., Mazauric, V., Maïzi, N. Increasing shares of intermittent sources in Reunion Island: Impacts on the future reliability of power supply. *Renewable and Sustainable Energy Reviews* 46, 120–128, 2015.

[6] Fesquet F, Juston P, Garzulino I. Impact and limitation of wind power generation in an island power system. In: *IEEE Bologna power technical conference*; 2003.

[7] Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable

electricity sources: an updated review. *Energy Sustain Dev.* 14, 302-14, 2010.

[8] Delfanti M, Falabretti D, Merlo M, Monfredini G. Distributed generation integration in the electric grid: energy storage system for frequency control. *J Appl Math.* 13, 2014.

[9] Weiss T, Schulz D. Development of fluctuating renewable energy sources and its influence on the future energy storage needs of selected European Countries. In: *4th International Youth Conference on Energy (IYCE)*, Hungary, 6-8; June 2013.

[10] Alam MJE, Muttaqi KM, Sutanto D. Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems. *IEEE Trans Power Syst* 28(4), 3874-3884. 2013.

[11] Hill CA, Such MC, Chen D, Gonzalez J, Grady WM. Battery energy storage for enabling integration of distributed solar power generation. *IEEE Trans Smart Grid* 3(2), 850-857, 2012.

[12] Ru, Y., Kleissl, J., Martinez, S. Storage Size Determination for Grid-Connected Photovoltaic Systems. *IEEE Transactions on Sustainable Energy*. 4(1), 68-81, 2011.

[13] Delfanti, M., Falabretti, D., Merlo, M. Energy storage for PV power plant dispatching. *Renewable Energy* 80, 61-72, 2015.

[14] Cervone, A., Santini, E., Teodori, S., Romito, D.Z. Impact of regulatory rules on economic performance of PV power plants. *Renewable Energy* 74, 78-86, 2015.

[15] Bridier, L., David, M., Lauret, P. Optimal design of a storage system coupled with intermittent renewables. *Renewable Energy* 67, 2-9, 2014.

[16] European Network of Transmission System Operators for Electricity. Operation Handbook. Technical Report, *European Network of Transmission System Operators for Electricity*; 2004.

[17] Bergen AR, Vittal V. Power system analysis, 2nd ed., Englewood Cliffs, NJ: *Prentice-Hall Series*; 2000.

[18] Bornard P, Pavard M, Testud G. Réseaux d'interconnexion et de transport: fonctionnement (in French). *Techniques de l'ingénieur 2005*;(D4091):1–12.

[19] Perez R, Lorenz E, Pelland S, Beauharnois M, Knowe GV, Hemker K, et al. Comparison of numerical weather prediction solar irradiance forecasts in the US, Canada and Europe. *Sol Energy* 2013;94:305e26.

[20] Almeida, M.P., Perpinan, O., Narvarte, L. PV power forecast using a nonparametric PV model. *Solar Energy* 115, 354–368, 2015.

[21] Lorenz E, Scheidsteger T, Hurka J, Heinemann D, Kurz C. Regional PV power prediction for improved grid integration. In: Special Issue: *25th EU PVSEC WCPEC-5*, Valencia, Spain, vol. 19(17); 2011. p. 757e71.

[22] Walton, S., Hassan, O., Morgan, K., Brown, M.R. Modified cuckoo search: A new gradient free optimisation algorithm. *Chaos, Solitons & Fractals* 44 , 710–718, 2011.

[23] Jeanty P., M. Delsaut, L. Trovalet, H. Ralambondrainy, J.D. Lan-Sun-Luk, M. Bessafi, P. Charton, J.P. Chabriat. Clustering daily solar radiation from Reunion Island using data analysis methods. *Renewable Energy and Power Quality Journal* (RE&PQJ) ISSN 2172-038 X, No.11, March 2013.