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Bidding and Optimization Strategies for Wind-PV Systems in Electricity Markets Assisted by CPS

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Abstract

The variability in non-dispatchable power generation raises important challenges to the integration of renewable energy sources into the electricity power grid. This paper provides the coordinated trading of wind and photovoltaic energy assisted by a cyber-physical system for supporting management decisions to mitigate risks due to the wind and solar power variability, electricity prices, and financial penalties arising out the generation shortfall and surplus. The problem of wind-photovoltaic coordinated trading is formulated as a stochastic linear programming problem. The goal is to obtain the optimal bidding strategy that maximizes the total profit. The wind-photovoltaic coordinated operation is modelled and compared with the uncoordinated operation. A comparison of the models and relevant conclusions are drawn from an illustrative case study of the Iberian day-ahead electricity market.

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Keywords: Coordinated bidding strategies, wind-PV power system, linear programming, day-ahead market

1. Introduction

For the next years power systems will likely show a substantially increased share of renewable energy of which a large portion will come from the variable renewable energy sources wind and photovoltaic [1]. Renewable energy grid integration under smart grid ambient and assisted by a cyber-physical system for supporting management decisions increased in the EU to fulfil the Energy–2020 initiative [2,3]. The growth of renewable energy technologies is a notary fact and the market for all renewables advanced in 2014 with wind power and photovoltaic taking the lead for capacity additions [4]. The number of countries with renewable energy targets and policies increased again in 2014. As of early 2015, at least 164 countries had renewable energy targets, and an estimated 145 countries had renewable energy support policies in place [1]. Policies provide subsidy and incentives for renewable energy which include feed-in-

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tariff, guaranteed grid access, green certificates, investments incentives, tax credits and soft balancing costs [5].

The paradigms of smart grid ambient and cyber-physical systems (CPS) [3] is a convenient upbringing for exploiting wind power, photovoltaic and facing the competition of electric energy market in order to obtain the economic revenue. But, the future smart grid ambient and CPS have a layered architecture of a cyber infrastructure accessing resilient power applications that are able to give security and reliability, having the ability to act in order to maintain and correct infrastructure components without affecting the service [6]. Also, this architecture based in the core of well design software, standing upon standards developed over the years, can offer a base tool to ease new standards and energy policies implementation [7,8]. A power systems CPS is schematically shown in Fig. 1.

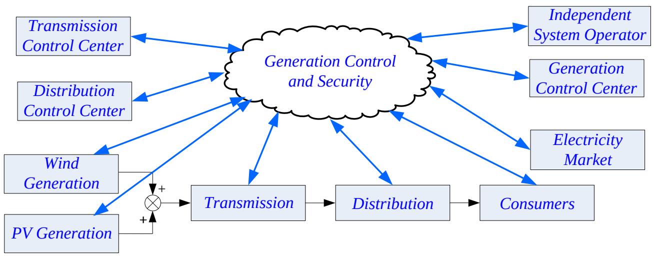


Fig. 1. Layout of the power systems cyber-physical infrastructure.

In Fig. 1 the CPS, consisting of electronic field devices, communication networks, substation automation systems, and control centers, is embedded throughout the physical power system for efficient and reliable generation, transmission, and distribution of power. The control center is responsible for monitoring in real-time, control, and operational decision making. The independent system operators perform coordination between power utilities, and dispatch commands to their control centers. Power producers participating in electric energy markets also interact with the independent system operators to support market functions based on real-time power generation, transmission, and demand.

A power producer in restructured electricity market is an entity owning power resources and participating in the market with the target of fronting the challenges of completion and uncertainty on electricity prices in order to achieve profit. Extra challenges for a wind–PV system owner come from the uncertainty on the availability of wind and solar resources meaning uncertainty in complying with power contracts [9]. The closing of the market defines power trading and price. In an attempt to reduce uncertainty from renewable energies, producers are required to provide day-ahead schedules of their generation. However, the remuneration depends on the conformity achieved on the level of the real deliver with the accepted value of the bid at the closing of the market. In absence of conformity, economic penalization for imbalances is due to happen [10]. A power producer problem from non-dispatchable renewable energy sources (namely solar and wind) aims to find the optimal energy bids in a electricity market featuring financial penalties for energy imbalance [10], in order to maximize its revenue, reducing the risk of deviations and consequently penalties for imbalances. A photovoltaic power system is designed to operate in residential appliances [11], and with the use of storage devices. For wind power is proposed the use of stochastic optimization tools or work together with a hydro generation company to reduce the imbalances [12]. Joint operation of the uncertain renewable energy resources and other units is another method which can be used to reduce the imbalance costs [13]. In [14], the development of bidding strategies is investigated for a wind farm owner and a deterministic MILP approach for its optimal operation is proposed. Surveys [15,16,17] reveal the absence of treatment of a coordinated configuration between wind and photovoltaic systems. In [18,19], linear programming is proposed for a wind energy problem instead of mixed-integer nonlinear programming. Thus, stochastic linear programming can be also proposed for the coordination of wind and photovoltaic systems.

So, the contributions of this paper are: a methodology to reduce the volatility and imbalances of wind and photovoltaic power using stochastic linear programming (LP); the coordination of wind and PV systems, presenting a single offer in the day-ahead market improving profit and reducing imbalances. This paper is organized as follows: Section 2 presents the problem formulation. Section 3 presents the case study. Finally, concluding remarks are given in Section 4.

Nomenclature

Sets and indexes:

Ω, ω	Set and index of scenarios
T, t	Set and index of periods in the time horizon

Constants:

λ_t	Day-ahead market-clearing price in period t
λ_t^+	Positive imbalance price in period t
λ_t^-	Negative imbalance price in period t
λ_t^{DN}	Price for excess of energy resulting of balancing market in period t
λ_t^{UP}	Price for deficit of energy resulting of balancing market in period t
r_t^+	Ratio between positive imbalance price and day-ahead market price in period t
r_t^-	Ratio between negative imbalance price and day-ahead market price in period t

$P_{t\omega}^{PV}$	Photovoltaic generation in period t and scenario ω
P_t^W	Wind generation in period t and scenario ω
$P^{PVmáx}$	Maximum power capacity of photovoltaic system
$P^{Wmáx}$	Maximum power capacity of wind system
c^{PV}	Photovoltaic marginal cost
c^W	Wind marginal cost
π_ω	Probability of each scenario ω
Continuous variables:	
P_t	Energy traded of the coordination of wind–PV system
P_t^{PV}	Energy traded of the PV system in period t
P_t^W	Energy traded of the wind system in period t
$\Delta_{t\omega}$	Total energy deviation of coordination of wind-PV system in period t and scenario ω
$\Delta_{t\omega}^{PV}$	Energy deviation of PV system in period t and scenario ω
$\Delta_{t\omega}^{W}$	Energy deviation of wind system in period t and scenario ω
$\Delta_{t\omega}^{+}$	Positive energy deviation of coordination of wind-PV system in period t and scenario ω
$\Delta_{t\omega}^{-}$	Negative energy deviation of coordination of wind-PV system in period t and scenario ω
$\Delta_{t\omega}^{PV+}$	Positive energy deviation of PV system in period t and scenario ω
$\Delta_{t\omega}^{PV-}$	Negative energy deviation of PV system in period t and scenario ω
$\Delta_{t\omega}^{W+}$	Positive energy deviation of wind system in period t and scenario ω
$\Delta_{t\omega}^{W-}$	Negative energy deviation of wind system in period t and scenario ω

2. Problem Formulation

Wind and PV energy are non-dispatchable and plagued by the major uncertainties that constitutes wind and solar irradiation availability. In addition to the intermittence and variability of wind and solar irradiation the wind–PV power producer must also cope with uncertain market prices. Thus, the market strategy of a coordinated wind–PV system producer must take into account these uncertainties in order to maximize its revenue for trading energy in day-head electricity markets, otherwise if not conveniently addressed it is possible to occur losses on profit due to imbalances penalties. The coordination of wind and PV energy can mitigate some of these uncertainties faced by the power producer working like a complement to each other.

2.1. Imbalance prices

System imbalance is defined as a non-null difference between the energy demand and the energy offer. The power producer is assumed to be a responsible entity and pay the market imbalance price for any contribution to the global system imbalance. If there is an excess of delivered energy in the power system, the system imbalance is positive, otherwise the system imbalance is negative. In the electricity market in Iberian Peninsula, like in the rest of European electricity markets, is defined a price for the positive energy deviation and a price for the negative energy deviation for each time period. In addition, these prices depends on the imbalances in the whole power system. Thus, if the system imbalance is positive, i.e., excess of generation, the power producers with excess of generation can sell its excess of generation in the balancing market at a price smaller than the day-ahead market and the producers with deficit of generation pay just the price equal to the day ahead market. The prices are as follow:

$$\lambda_t^+ = \min(\lambda_t, \lambda_t^{DN}) \tag{1}$$

$$\lambda_t^- = \lambda_t \tag{2}$$

In (1) and (2), λ_t^+ and λ_t^-, are applied in the balancing market to the energy deviations, λ_t is the day-ahead market-clearing price and λ_t^{DN} is the price of the energy of offers in exceeds. Otherwise, if the system imbalance is negative, the price are as follow:

$$\lambda_t^+ = \lambda_t \tag{3}$$

$$\lambda_t^- = \max(\lambda_t, \lambda_t^{UP}) \tag{4}$$

In (4), λ_t^{UP} is the price of the energy that needs to be added to the system.

The profit of a power producer that offers and gets a certain amount of energy for hour t is as follows:

$$PR_t = \lambda_t P_t + I_t - cP_t \tag{5}$$

In (5), P_t is the power trade by the power producer in the day-ahead market, I_t is the imbalance income resulting from the balancing process and may be negative, i.e., it may represent a cost. c is the marginal cost of the system.

The total deviation incurred by the producer in period t is as follows:

$$\Delta_t = P_{\omega t} - P_t \tag{6}$$

where $P_{\omega t}$ is the total actual power in period t. So, I_t is as follows:

$$I_t = \lambda_t^{+} \Delta_t , \Delta_t \geq 0 \quad (7)$$

$$I_t = \lambda_t^{-} \Delta_t , \Delta_t < 0 \quad (8)$$

In (6), a positive deviation means the actual production is higher than the traded in the day-ahead market and a negative deviation means an actual production lower than the traded. Therefore, λ_t^{+} is the price at which the wind and solar producer will be paid for its excess of generation and λ_t^{-} the price to be charged for the deficit of generation. Let:

$$r_t^{+} = \frac{\lambda_t^{+}}{\lambda_t}, r_t^{+} \leq 1 \quad (9)$$

$$r_t^{-} = \frac{\lambda_t^{-}}{\lambda_t}, r_t^{-} \geq 1 \quad (10)$$

(9) and (10) are the positive and negative imbalance price ratio as result of the ratio of the positive imbalance price by the day-ahead market and the ratio of the negative imbalance price by the day-ahead market, respectively. Then:

$$I_t = \lambda_t \, r_t^{+} \Delta_t , \Delta_t \geq 0 \quad (11)$$

$$I_t = \lambda_t \, r_t^{-} \Delta_t , \Delta_t < 0 \quad (12)$$

2.2. Objective function

The market prices, wind power and photovoltaic power are considered as stochastic processes and represented as a set of scenarios each one. So, with these uncertainties, is considered a set of Ω scenarios for every hour. Each scenario ω has the probability of occurrence π_ω.The stochastic LP formulation of the problems to support the biding strategies in an uncoordinated assessment of wind power and PV power systems are similar maximization problems respectively as follow:

- *Wind power:*

$$\sum_{\omega=1}^{\Omega} \sum_{t=1}^{T} \pi_\omega \left(\lambda_{t\omega} P_t^{W} + \lambda_{t\omega} r_{t\omega}^{+} \Delta_{t\omega}^{W+} - \lambda_{t\omega} r_{t\omega}^{-} \Delta_{t\omega}^{W-} - c^{W} P_{t\omega}^{W} \right) \quad (13)$$

subject to:

$$0 \leq P_t^{W} \leq P^{Wmax}, \forall t \quad (14)$$

$$\Delta_{t\omega}^{W} = P_{t\omega}^{W} - P_t^{W} , \forall t, \forall \omega \quad (15)$$

$$\Delta_{t\omega}^{W} = \Delta_{t\omega}^{W+} - \Delta_{t\omega}^{W-} , \forall t, \forall \omega \quad (16)$$

$$0 \leq \Delta_{t\omega}^{W+} \leq P_{t\omega}^{W} , \forall t, \forall \omega \quad (17)$$

$$0 \leq \Delta_{t\omega}^{W-} \leq P^{Wmax} - P_{t\omega}^{W} , \forall t, \forall \omega \quad (18)$$

- PV power:

$$\sum_{\omega=1}^{\Omega}\sum_{t=1}^{T}\pi_{\omega}\left(\lambda_{t\omega}P_{t}^{PV}+\lambda_{t\omega}r_{t\omega}^{+}\Delta_{t\omega}^{PV+}-\lambda_{t\omega}r_{t\omega}^{-}\Delta_{t\omega}^{PV-}-c^{PV}P_{t\omega}^{PV}\right) \quad (19)$$

subject to:

$$0\le P_{t}^{PV}\le P^{PVmax},\forall t \quad (20)$$

$$\Delta_{t\omega}^{PV}=P_{t\omega}^{PV}-P_{t}^{PV},\forall t,\forall\omega \quad (21)$$

$$\Delta_{t\omega}^{PV}=\Delta_{t\omega}^{PV+}-\Delta_{t\omega}^{PV-},\forall t,\forall\omega \quad (22)$$

$$0\le\Delta_{t\omega}^{PV+}\le P_{t\omega}^{PV},\forall t,\forall\omega \quad (23)$$

$$0\le\Delta_{t\omega}^{PV-}\le P^{PVmax}-P_{t\omega}^{PV},\forall t,\forall\omega \quad (24)$$

The stochastic LP formulation for the coordinated Wind-PV system is specified by the maximization of the objective function given as follows:

$$\sum_{\omega=1}^{\Omega}\sum_{t=1}^{T}\pi_{\omega}\left(\lambda_{t\omega}P_{t}+\lambda_{t\omega}r_{t\omega}^{+}\Delta_{t\omega}^{+}-\lambda_{t\omega}r_{t\omega}^{-}\Delta_{t\omega}^{-}-c^{PV}P_{t\omega}^{PV}-c^{W}P_{t\omega}^{W}\right) \quad (25)$$

The maximization is subjected to constraints as follows:

$$0\le P_{t}\le P^{PVmax}+P^{Wmax},\forall t \quad (26)$$

$$\Delta_{t\omega}=\left(P_{t\omega}^{PV}+P_{t\omega}^{W}\right)-P_{t},\forall t,\forall\omega \quad (27)$$

$$\Delta_{t\omega}=\Delta_{t\omega}^{+}-\Delta_{t\omega}^{-},\forall t,\forall\omega \quad (28)$$

$$0\le\Delta_{t\omega}^{+}\le P_{t\omega}^{PV}+P_{t\omega}^{W},\forall t,\forall\omega \quad (29)$$

$$0\le\Delta_{t\omega}^{-}\le(P^{PVmax}+P^{Wmax})-(P_{t\omega}^{PV}+P_{t\omega}^{W}),\forall t,\forall\omega \quad (30)$$

In (26) the limit of offers is the maximum capacity in the coordinated wind–PV power system. In (27) to (30) $\Delta_{t\omega}$ is decomposed into the sum of the positive $\Delta_{t\omega}^{+}$ and the negative $\Delta_{t\omega}^{-}$ imbalances. With these decomposition binary variables is not necessary due to the nature of the optimization problem tending to minimize the imbalance cost. The stochastic linear programming problem guarantees that the optimal solution is achieved with one of the variables of the imbalances $\Delta_{t\omega}^{+}$ or $\Delta_{t\omega}^{-}$ equal to zero due to the fact that $r_{t\omega}^{+}\le 1$ and $r_{t\omega}^{-}\ge 1$. If the system imbalance is negative the wind–PV producer is penalized for the deficit of energy generated below the energy traded in the day-ahead market, so the term $\lambda_{t\omega}r_{t\omega}^{+}\Delta_{t\omega}^{+}$ is null and the term $\lambda_{t\omega}r_{t\omega}^{-}\Delta_{t\omega}^{-}$ is subtracted from the revenue in the situation of no deviation, $\lambda_{t\omega}P_{t}$. If the system imbalance is positive, the wind–PV producer is penalized for the energy generated above the energy traded in the day-ahead market, so that the term $\lambda_{t\omega}r_{t\omega}^{-}\Delta_{t\omega}^{-}$ is null and the term $\lambda_{t\omega}r_{t\omega}^{+}\Delta_{t\omega}^{+}$ is added to the revenue in the situation of no deviation. In (29) the maximum positive deviation occur when the wind–PV producer does not sell any amount of energy in day-ahead market, $P_{t}=0$, but its final production is

$P^{PV}_{t\omega} + P^{W}_{t\omega}$ in the same time period *t*. In (30), the maximum negative deviation occur when the wind–PV producer sells the equivalent to the maximum capacity $P^{PVmax} + P^{Wmax}$, but its final production is $P^{PV}_{t\omega} + P^{W}_{t\omega}$.

3. Case Study

The data for the case study are from a coordinated wind–PV system deployed in the Iberian Peninsula with a wind farm of 100 MW of rated power and a PV power plant of rated power of 50 MW. The data for day-ahead prices and price multipliers r^+_t e r^-_t are from the Iberian electricity market [20]. The coordination is on an hourly basis with a 24 h range for the day-ahead market. The plants share a line to connect to the grid. The proposed stochastic linear programming approach provides the maximization of the coordinated wind–PV system taking into account 10 scenarios for wind power, 10 for solar power, 10 for day-ahead market prices and 10 for imbalance prices. The marginal cost of the wind farm is equal to 16.26 €/MWh and the marginal cost of the PV system is 28.6 €/MWh according to [21]. The coordinated wind–PV system aims to achieve the optimal single bid for the day-ahead market. The coordinated stochastic linear programming problem is programmed in the software GAMS.

The day-ahead market-clearing price scenarios are shown in Fig. 2.

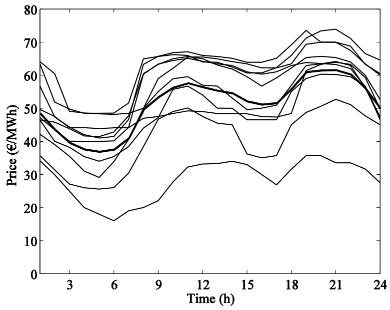
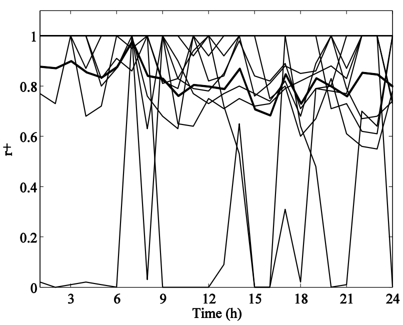
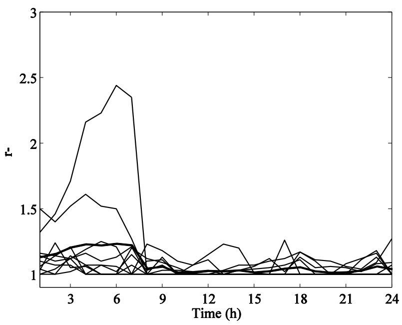


Fig. 2. Day-ahead market price scenarios and average scenario (thick line).

The imbalance price multipliers r^+_t and r^-_t scenarios are shown in Fig. 3.



(a)



(b)

Fig. 3. Imbalance price multipliers and average scenario (thick line); (a): r^+_t, (b): r^-_t.

The wind and PV generation scenarios are obtained using the total energy produced along the 24 h of the wind farm scaled to the maximum power of 100 MW and of the PV system scaled to 50 MW. The wind and PV generation scenarios are shown in Fig. 4.

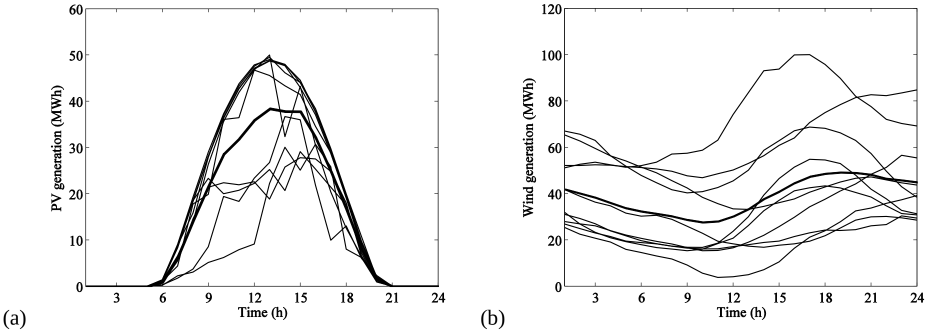


Fig. 4. Generation scenarios and average scenario (thick line); (a): PV, (b): wind.

The optimal bid for the uncoordinated configuration, as result of (13) to (24) is shown in Fig. 5.

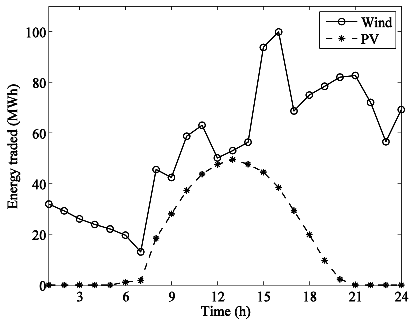


Fig. 5. Energy traded; PV: dashed-line, wind: line.

The optimal single bid for the coordinated wind–PV system traded for the period of the 24 h is the result of the formulation from (25) to (30). The comparison of the amount of energy traded in day-ahead market and the energy deviation by the uncoordinated configuration and the coordinated wind–PV configuration is shown in Fig. 6.

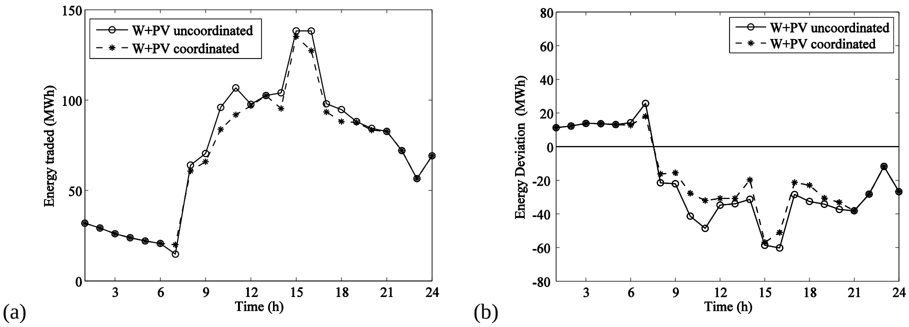


Fig. 6. (a) Energy traded; (b) Energy deviation.

In no sun periods the energy traded for the wind–PV coordinated configuration is equal to the energy traded for the uncoordinated in the same period. For only once the coordinated configuration offers more energy. In the other cases the coordinated configuration offers less energy than the uncoordinated configuration.

The expected results with and without coordination are shown in Table 1.

Table 1. Results with and without coordination

Case	Energy traded (MWh)	Profit (€)	CPU Time (s)
Wind	1,312.91	31,827.84	5.54
PV	419.14	8,500.39	5.18
Total Wind-PV	1,732.05	40,328.23	-
Coordinated Wind-PV	1,666.38	40,425.09	16.54

Table 1 shows that the amount of energy traded in the day-ahead market is smaller for the coordinated system than for the total wind–PV uncoordinated. However, wind–PV coordinated coordination provides an improvement on total profit in comparison with the total wind–PV uncoordinated due to the reduction in the deviations of the coordinated configuration. The coordinated wind–PV configuration can absorb more generation volatility than the uncoordinated configuration and so that reduce energy deviations.

4. Conclusions

This paper presents the coordination of wind–PV systems for a power producer with the aim of trading energy with a single bid for aggregating wind and PV power production. A stochastic linear programming approach for solving the offering strategy of the power producer in a deregulated market is discussed and find how the coordination of wind and photovoltaic systems can reduce the energy deviations, reduce the wind–PV producer risk for trading energy in electricity markets and improve its profits in comparison with the uncoordinated strategy. The main result is the optimal single bidding strategy for wind and solar producer facing the wind, solar irradiation and price uncertainties, as well the system imbalances which affect the price in case of deviations between the energy traded in the day-ahead market and the actual energy produced by the wind and solar producer.

The wind–PV coordinated configuration can be a good strategy for renewable energy producers trying to cope with uncertainties of both wind and solar irradiation. Stochastic linear programming is a suitable approach to address the uncertainties of wind power, photovoltaic power and market prices in modelling via a set of scenarios.

Acknowledgements

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