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Optimal sizing of hybrid wind-photovoltaic plants: A factorial analysis

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ABSTRACT

This research attempts to determine the optimal size (in terms of profitability) of a photovoltaic (PV) plant that is going to be added to an existing wind installation. The analysis carried out is based on a real sample of 62 wind facilities located in 25 Spanish provinces in 2021. Given the hourly energy generated throughout the year by the wind facility and its grid capacity, the optimal power of the PV plant in the hybrid facility will be the one that allows maximising the net present value of the investment, i.e., the one that allows to better adjust (in economic terms) the PV production to the characteristics of the wind farm. For our empirical analysis we need data on the day-ahead energy market price, on the grid capacity and hourly production (in the day-ahead energy market) of the 62 wind farms analysed, and on the hourly PV production in the Spanish provinces where those wind farms are located. In average terms, to maximise the Net Present Value (NPV) per € invested, the optimal PV power to be added to an existing wind farm should be 8% of the wind power already installed. The averages of the financial indicators for optimal PV sizing are promising (discount rate of 7%): NPV per € invested is 1.89, NPV is M€ 23.5, discounted payback is 4.85 years, and the internal rate of return index is 25.6%. To conclude our empirical analysis, we estimate a multilevel regression model for the hourly wind production. The regression model shows, among other results, that one more MW of wind power translates into an increase in wind generation of 0.31 MWh. Our findings will help the design of hybrid plants without neglecting the economic aspect.

Introduction

A hybrid power plant is any facility that combines different energy production systems. Hybrid plants may be with or without storage, but it is essential that the entire generation is managed by a single company through a single connection point and with the same control and monitoring system. According to Timmerman et al. [50], the different energy sources (sun, wind, ground heat, biomass, biofuel, hydrogen, fossil fuel, organic waste, waves, waste heat, etc.) give rise to many other energy production technologies (solar photovoltaic, solar thermal, wind turbine, geothermal, heat pump, wave power, fuel cell, boiler, gasifier, organic Rankine cycle, etc.). Initially, any feasible combination of these technologies could lead to a hybrid power generation plant. Within the different possible combinations, Lian et al. [28] collect those that would have a real penetration in the market, according to their levels of operational efficiency and economic viability –Rekioua [40] also discusses different hybrid plant options–.

The criteria for the start-up of a hybrid generation plant using renewable sources are related to different factors, such as the availability of land, the funds necessary to carry out the investment, the technical and economic feasibility, the profitability and return on investment, and the restrictions linked to legal issues and environmental impact. The start-up of hybrid plants that combine wind and photovoltaic technologies (and use accumulation systems) appears to be an interesting option for Hansen et al. [23] or Sinha and Chandel [46]. Some authors argue for the existence of a support framework for renewable energies –hybrid plants are obviously part of the analysis–. Zimmermannová et al. [54] are in favour of maintaining public funding as an incentive for solar electricity projects. Palage et al. [36] find a positive correlation between public support and the take-off of the renewable sector. For their part, Lacal-Arantegui and Jäger-Waldau [27] describe how the energy policy framework in the European Union is contributing to the deployment of clean energies. In any case, despite the evident and growing interest of governments in promoting renewable energy generation facilities (see, in Spain, the royal decree-law 23/2020 of measures in the field of energy and in other areas for the economic reactivation), regulatory bodies must establish the criteria that have to be met to obtain the access and connection permits to the grid. The capacity of the network mandates, of course, and defines the size of generation plants.

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There is a vast literature on hybrid installations with energy storage. This subject is outside the scope of this study; however, we would like to highlight the abundant existing literature on this matter. Most of the studies make technical (not economic-financial) contributions. Thus, Mazzeo *et al.* [33] design a hybrid system plus batteries to supply: a heat pump, electric office devices and an electric vehicle charging station. For Al-Hadi et al. [6] the interest of this type of facility lies in its purpose for the energy supply of grid connected buildings. Mazzeo et al. [32] propose an algorithm to optimally manage the charging strategy of the Home to Vehicle and Vehicle to Home technologies in a stand-alone context where the energy system is fed by a hybrid plant with batteries. For their part, Hesse et al. [24] develop a method for optimizing the sizing of battery systems based on the demand curve and the existing photovoltaic production –in this field, see also Ballesteros-Gallardo et al. [9]–, while Abbassi et al. [2] develop a method for sizing batteries in isolated wind-photovoltaic systems. Ghorbanzadeh et al. [21] analyse the charge degradation process of lithium-ion batteries in off-grid wind-battery renewable energy systems. More recently, Belaid et al. [10] analyse the feasibility of a wind energy installation with battery, determining that Hybrid MPPT (Maximum Power Point Tracking) selects the best control technique combination that provides the maximum power value and minimises the stress of batteries. Finally, the variability in the solar renewable supply can also be dismissed with hydroelectric storage systems, an approach defended by authors such as Petrollese *et al.* [37] and Shabani *et al.* [45], who carry out studies to evaluate the feasibility of these facilities both in the cases of PV tracking and non-tracking systems.

Several authors have analysed the economic viability of the use of batteries in renewable energy installations. For instance, Naumann [34] and Sahu et al. [42] adopt a technical–economic approach. The first focuses on battery degradation, while the second highlights the interest of battery hybrid systems for use in isolated rural areas. For their part, Khan et al. [25] focus on the benefits associated with the extra energy provided by these kinds of systems –other works that introduce, to a greater or lesser extent, an economic approach are Ekren and Ekren [19], Tervo et al. [49], Comello and Reichelstein [16], Xie et al. [53], and Belouda et al. [11].

We have found several articles in the literature which analyse the sizing of hybridisation in electricity generation technologies, a topic closer to the object of this study than that of hybridisation with storage. Thus, Lian et al. [28] analyse different types of existing energy combinations, possible indicators for their evaluation, and different methodologies to determine the optimal size of these hybrid plants, both connected to or isolated from the grid. These authors suggest including in the objective function for the decision-making indicators related to: economic factors –as our study does–, operational reliability of the installation, social variables, and environmental factors. Sultan et al. [47] develop a metaheuristic optimization model to design a hybrid photovoltaic-wind-fuel cell system. Acuña et al. [4], meanwhile, complete a multi-objective study with two objective variables: the cost of installation and the maximum expected energy. For their part, Goncalves et al. [22] analyse the optimal sizing of a photovoltaic plant coupled to a wind power plant, concluding, for the hypothetical case of a hybrid plant located in the Petrolina region (Brazil), that 70% of the nominal power of the hybrid plant should be solar. Anoune et al. [8] determine the size of a Hybrid plant by maintaining a constant storage temperature of bitumen. Al-Ghussain et al. [5] size a hybrid plant for a case study (Al-Tafilah cement factory). Mahmoudi et al. [30] harness fuzzy logic to optimise the sizing of hybrid plants, while Rezaei et al. [41] determine the optimal location of a wind-solar hybrid plant in Fars (Iran) considering four economic criteria, and geological, social, and natural disasters conditions. Mazzeo et al. [31] also include green hydrogen in the analysis. Finally, Acuna et al. [3] propose a reliability indicator for hybrid plants based on the minimum hourly electric power obtained from the wind and solar radiation using a probabilistic approach.

Among the different combinations of existing energies, solar and wind appear as the most relevant solution due to their “grid parity” and the complementarity of their generation curves –together they generate a lower Levelized Cost of Energy (LCOE)–. The installation of a photovoltaic (PV) plant together with an existing wind farm, considering the existing grid capacity and the complementarity between wind and PV generation, results in a hybrid plant capable of injecting the maximum admitted power into the grid in a greater number of hours than if it were a plant equipped only with wind or solar energy. Ludwig et al. [29] analyse this type of facilities; they consider the loss of PV yield due to shading of the wind turbine to be negligible and conclude that hybrid installations are more interesting than stand-alone PV or wind power plants. The combination of wind and solar energies, both on-shore and off-shore, is also studied by Campana et al. [15]. These authors point out the advantages of floating systems (with tracking or fixed axis) in offshore wind plants. Anyway, the energy production in both photovoltaic and wind power plants is constricted to the variability in environmental conditions, and this variability is a random factor that still conditions the regularity in the energy generation of this type of facility. A deeper analysis of the influence of climate conditions on the power generation can be found in Bozonnat and Schlosser [13], Al-Ghussain et al [5], Sanjari et al [43], Prema *et al.* [38] and Drikakis *et al.* [18].

The scope of our study is to determine the optimal size of a photovoltaic facility installed within the existing wind power plant to take advantage of the existing feed-in capacity in those hours that are not fully covered by wind power generation. In this way, energy production would converge towards the maximum nominal power that the grid can afford. The optimal size of the PV plant will be determined according to an economic criterion; this is, given the hourly energy generated throughout the year by the wind facility and its grid capacity, the optimal power of the PV plant in the hybrid facility will be the one that allows maximising the net present value of the investment; i.e., the one that allows to better adjust (in economic terms) the PV production to the characteristics of the wind farm. Note that, in our business proposal, the investor saves the cost of grid connection, since the wind farm is already connected to the grid and in operation –the value of a MW of grid connection is around 100,000 € in Spain–.

We have found it difficult to find studies in this field that take an ex-post approach where the wind farm is already designed, installed and in operation. Most of the reviewed studies focus on the ex-ante design of hybrid plants. In fact, we have not found in the reviewed literature a work that proposes a simple model on an existing wind farm that determines the optimal combination of hybrid PV-wind power that maximises the net present benefit of the PV investment, as this work does. For instance, Razmjoo & Davarpanah [39] analyse four different models of hybrid plants in the city of Damghan (Iran), concluding that the PV-Wind combination is the most interesting one (based on power generation and environmental pollution criteria). However, they do not dimension, as this paper does, the power rate between wind and solar installations. Sekhar and Kumaresan [44] propose a hybrid power system (with solar and wind technologies, among others) for installation in isolated locations but without proposing a financial analysis of the return on the investment. For their part, Tadjine et al. [48] determines the optimal sizing of both generators (wind turbine and solar plant) from the initial stage (adjusting the sizes of both technologies). Unlike these authors, we develop the analysis starting from a fixed wind farm capacity, which can be more realistic in certain situations.

Our methodology for sizing a PV plant in a hybridisation scenario addresses a real-life problem, since it is applied to real wind power plants that are already in operation (each with a corresponding size and grid connection). Specifically, the study is based on a real sample of 62 wind power plants located in the Spanish geography. For each wind plant hybridised with solar energy, different PV powers are simulated (from 0.1 MW to 50 MW in 0.1 MW increments) to find the value that maximises the Net Present Value (NPV) of the investment. The applicability of our methodology is versatile, since it can be applied to other

Table 1
Statistical description of the variables.

Variable	Obs.	Mean	Std. Dev.	Min	p25	Median	p75	Max
Wind farm power (MW)	62 units	27.4	17.11	1.7	16.0	23.9	37.3	99.0
Wind farm production (MWh)	62 units × sales offers	9.20	11.16	0.1	1.4	5.2	12.5	99.0
Equivalent hours (at the wind power)	62 units	2393.5	1290.9	167	1548	2275	3050	5790
Gap production in the wind farms	62 units × hours of sun	20.55	15.03	0.10	10.40	18.20	27.9	99.0
1-MWp PV production (MWh)	25 provinces × hours of sun	0.32	0.20	0.00	0.12	0.35	0.5	0.71
Day-ahead market price	8760 h	111.9	74.7	0.01	60.88	89.5	157.6	409

studies which consider other energy sources (hydrogen, geothermal, wave, etc.) as long as their hourly productions and network capacities are known. Additionally, our optimal sizing analysis is complemented by an explanatory econometric analysis of the wind energy production that allows reaching conclusions of interest about its relationship with the PV production or the capacity of the wind farm (*ceteris paribus*). This paper aims to align with the objectives of sustainable development of the United Nations, in particular objective 7°, by which a greater proportion of energy based on renewable sources is pursued by 2030, doubling the world rate of energy efficiency and improving the research strategy towards less polluting energies.

The rest of the paper continues as follows: Section 2 consists of three sub-sections. Subsection 2.1 provides the data description. Subsection 2.2. explains the financial methodology used to determine the optimal size of the PV being part of a hybrid installation. Subsection 2.3. shows the methodology of the multilevel regression model, which will be used to find the determinants of wind power production. In Section 3 the main financial and operating results of the proposed methodologies are described. Finally, Section 4 concludes.

Materials and methods

Data of the study

In Spain there is a total of 1267 wind facilities in more than 800 townships, which provide 27.446 MW, 21,9% of the total Energy consumed[1]. There is a growing interest in this type of plants, analysing aspects such as the maximum possible generation based on what is admissible by the grid, the power installed and the climatic conditions of the area, the possibility of complementing the installation with the support of other energy sources, and the profitability of the resulting hybrid plant, as discussed in this work. Of the total number of wind farms existing in Spain in 2021, in this study we have identified the geographical location of 62 of them, which constitute our study sample.

Two sources of information have been used to carry out our research: (1) PVGIS (Photovoltaic Geographical Information System) is a free access tool developed by the European Commission that allows the determination of the electrical production of a photovoltaic plant based on the specific solar irradiation and climatology of the geographic location. (2) OMIE [35] (Iberian Energy Market Operator) publishes the day-ahead market electricity price and the installed power and hourly energy production of the studied wind facilities in 2021. The European Union has established a framework for the regulation of the European electricity sector until 2030, designating a NEMO (Nominated Electricity Market Operators) in each of the Member States[7]. In Spain and Portugal, OMIE is the company in charge of managing the wholesale electricity market (day-ahead and intraday markets) in the Iberian Peninsula. Among other functions, OMIE supervises the communication to each agent of the information related to their corresponding buying and selling units and publishes the (day and intraday) supply and demand curves.

Table 1 contains the descriptive statistics of the variables used in our study. As shown in the table, the average capacity of the wind facilities in the sample is 27.4 MW (with a standard deviation of 17.11 MW), while their wind production shows an average value of 9.2 MWh (standard deviation of 11.16 MWh), far from the average wind capacity –Fig. 1 shows the distribution of wind farm capacity; only two wind facilities in the sample exceed 50 MW capacity–. We have calculated the

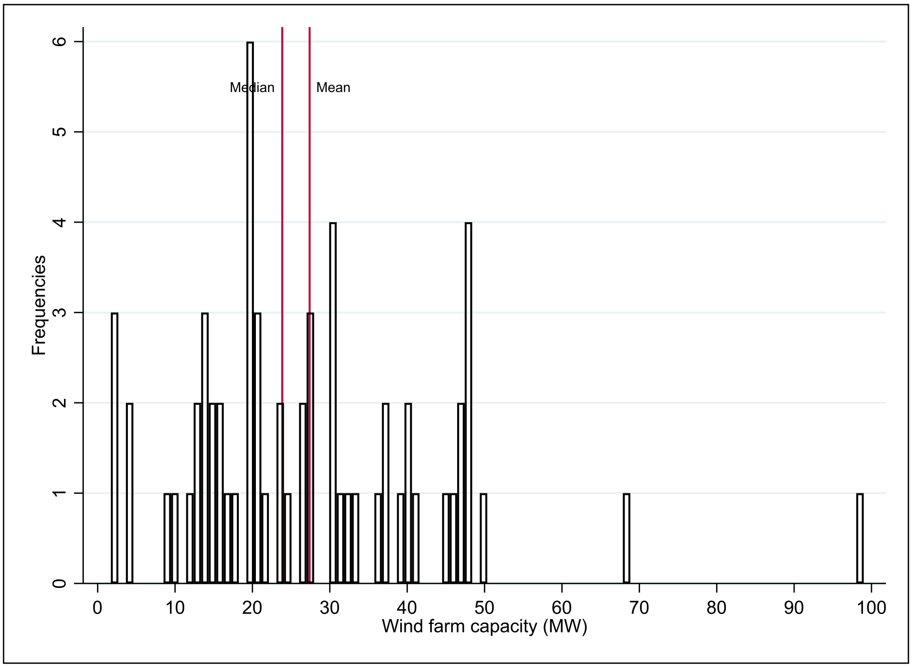


Fig. 1. Distribution of wind farm capacity.

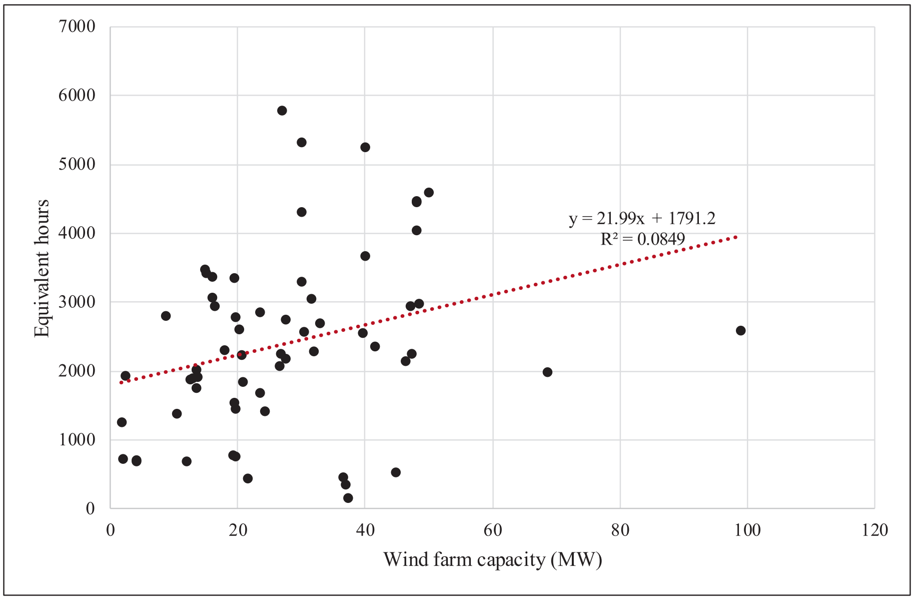
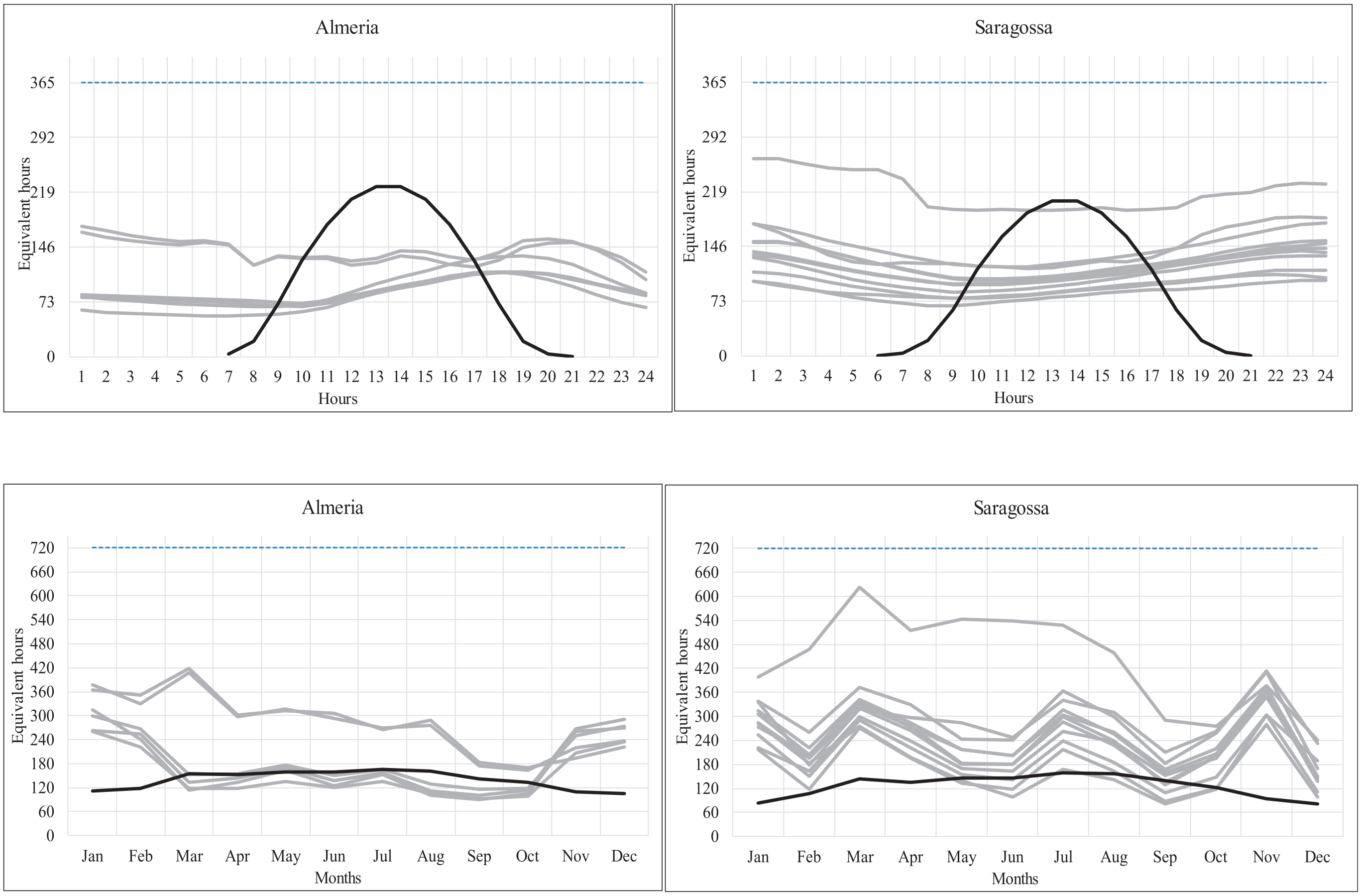


Fig. 2. Wind facility capacity and equivalent hours (to the capacity of the wind facilities).



(b)

Fig. 3. Evolution of equivalent hours (wind vs. photovoltaic).

equivalent hours of each wind farm as the ratio between annual energy production and installed capacity (MW). The mean and median of the equivalent hours are 2393.5 and 2275 respectively, although some generation units have been able to operate at full capacity for more than 4000 h. For its part, the gap production between capacity (C_j) and production ($W_{j,h}$) is 20.5 MWh on average in the year 2021, with a standard deviation of 15.03 MWh. It is also observed that the production of solar energy for a 1-MW plant, 0.32 MWh of average production, is relatively small in relation to the observed wind production. Finally, the daily market price stands, on average, at 111.9 €/MWh, although the standard deviation of the variable is 74.7 €/MWh –this price has fluctuated between 0.01 and 409 €/MWh in 2021–.

The scatter plot of Fig. 2 relates the wind facilities capacity to their annual equivalent hours. The regression line shows a significant (at a 95% confidence level) positive relationship between the power and the volume of equivalent hours, although the goodness-of-fit (coefficient of determination, R^2) is small due to the scattering of the point cloud data.

Fig. 3(a) and 3(b) show the distribution of the equivalent hours for both technologies (wind and PV) by hours of a day and months of a year, respectively. Specifically, Fig. 3(a) shows how many hours out of the 365 h that each hour of the day represents throughout the year the generator would have needed to reproduce its accumulated production in that hour over the year if it had operated at full capacity. For its part, Fig. 3(b) shows how many hours, out of the 720 h that approximately each month has, the generator would have needed to reproduce its accumulated production in that month if it had operated at full capacity. For comparative purposes, we have represented a northern province (Saragossa) and a southern province (Almeria) of Spain. Specifically, we have represented the equivalent hours of a 1-MW PV plant (black lines in the figures) and the equivalent hours of those wind facilities in the sample that are located in those two provinces (grey lines in the figures). As can be seen, the PV curves of equivalent hours are more predictable than the wind curves. The central hours of the day and the spring-summer months are the ones with the highest PV production, which is why a greater volume of equivalent hours is needed to reproduce the production of the PV park; moreover, PV production is somewhat higher in Almeria (the southern province), which explains why its equivalent hour curves are slightly higher than those of Saragossa. The equivalent hours of the wind facilities show more irregular profiles, which depends on the province and, more specifically, on the exact location of the wind facility. In principle, those wind facilities with fewer equivalent hours –this is, with a lower ratio ‘energy production/capacity’– could benefit to a greater extent from the hybridization of technologies.

Optimal sizing of the photovoltaic installation

Hybrid plants that combine both wind and photovoltaic sources are of strategic interest, offering the possibility of compensating with solar generation the fall of wind generation below its grid capacity. In our analysis, we assume that the capacity of a wind facility is adjusted to the grid capacity set for that facility (C_j). The financial methodology to determine the optimal size of a PV plant in a hybrid facility can be expressed in the following steps:

1. Let $j = 1,\ldots,62$ be the wind installations of this study. Note that, from the total population of generators in the Spanish electricity market, we have been able to identify 62 wind facilities, which constitute the sample under study. We know the hourly energy offer of each wind facility j ($W_{j,h}$), their geographical location (province[1]), and their grid capacity (C_j) –for simplicity, a constant grid capacity is assumed throughout the investment time horizon.
2. Let $i = 1,\ldots,25$ be the PV facilities of the study. The 62 wind facilities in the sample are distributed throughout 25 Spanish provinces (out of a total of 50). The PVGIS tool allows estimating the expected value of the hourly PV production in these provinces (provinces where the hybridizations will take place).
3. The business idea consists of expanding the current hourly generation of an existing wind facility (in the day-ahead energy market) through the joint installation of a p-MW PV plant whose hourly energy generation is represented as $E^p_{i,h}$. To obtain this last variable, we have multiplied by 0.9 the PV production obtained from PVGIS (to consider the shadow effect caused by the wind facility[2]). The subscript $h = 1,\ldots,8760$ represents all the hours of the year analysed.
4. Let $n = 1,\ldots,62$ be the hybrid facilities of the study, which are formed by those pairs of PV and wind generation units that are located in the same province –note that there are as many hybridizations as the number of wind farms analysed–. We will call $\Delta E^p_{n,h}$ the vector of dimension 8760 × 1 (annual hours) that contains the effective increase in energy production for hybrid park n thanks to p-MW PV production; this is, the PV energy that can be sold within the hybrid plant (known C_j and $W_{j,h}$). This PV production follows the next scheme:
   a. If the sum of the energy generated by the wind facility ($W_{j,h}$) plus the energy generated by the p-MW PV plant ($E^p_{i,h}$) is greater than the grid capacity (C_j) –remember that $W_{j,h} \leq C_j$–, the effective (PV) energy increase ($\Delta E^p_{n,h}$) will be just what is needed to cover the gap between C_j and $W_{j,h}$.
   b. If the above sum is less than or equal to the grid capacity (C_j), then the effective (PV) energy increase will be all the energy generated by the PV plant in that hour ($\Delta E^p_{n,h} = E^p_{i,h}$); energy that may or may not be enough to cover the gap between C_j and $W_{j,h}$.
5. By using the wholesale market energy price in each hour h of the year (P_h), we can calculate the hourly revenue ($R^p_{n,h}$) of the hybrid plant n because of the increase in energy due to the installation of the p-MW PV plant:

$$R^p_{n,h} = \Delta E^p_{n,h} \mathrm{P_h} \tag{1}$$

Note that all hourly variables obtained must be calculated for each year of the investment time horizon –we have omitted the year subscript for the sake of model simplicity.

The financial analysis of hybrid plants calculates the Net Present Value and the Internal Rate of Return (IRR, NPV(k = IRR) = 0) for the sale of PV energy in each hybrid facility and simulated PV peak power p. Likewise, as different scale investment projects are analysed, the calculation of the NPV per € invested will also be considered. The analysis starts determining the lifespan of the hybrid installation (25 years in this study) and the discount rate required to update the cash flows of each possible project (k = 7%, regulated data for the electricity generation sector). The investment associated with the PV power plant i, relative to the wind power facility j, is determined by the CAPEX of the PV assets and their installation. A conservative approach is adopted, assigning CAPEX values of 500,000 €/MW –see Vartiainen et al. [52]–. Likewise, we assume that the annual OPEX is 2% of the investment –OPEX includes maintenance of components, module cleaning, grass cutting, land lease, insurance, grid fees, balancing, asset management, and various taxes.

Equation (2) and (3) respectively determine the initial cash flow ($CF_{n,0}$), which is given by the CAPEX of the p-MW PV system (I^p_i €/MW), and the annual cash flows $CF_{n,y}$ generated by that PV investment in the hybrid facility n:

$$CF^p_{n,0} = -I^p_i n = 1, \ldots, 62,\ p = 0.1,\ 0.2, \cdots, \mathrm{C}n \tag{2}$$

$$CF^p_{n,y} = \left(\sum_{h=1}^{8760} R^p_{n,h}\right) - OPEX^p_{n,y} = \left(\sum_{h=1}^{8760} R^p_{n,h}\right) - 0.02\cdot I^p_i \quad n = 1,..,62, \quad p = 0.1,\ 0.2,..,Cn, \quad y = 1,..,25 \tag{3}$$

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[1] Regions NUTS2. NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU [17].

[2] On the shadow effect, see the simulator of the Danish Wind Industry Association in: https://www.windpower.org/en/tour/env/shadow/index.htm.

C_n measures the capacity of the hybrid plant which is given by the grid capacity C_j of the corresponding wind farm. Once the cash flows are determined, the NPV of the *p*-MW PV plant *i* in the hybrid facility *n* is calculated as follows:

$$NPV_n^p = CF_{n,0} + \sum_{y=1}^{25} \frac{CF_{n,y}^p}{(1+k)^y} n = 1, \ldots, 62, p = 0.1, \cdots, \mathrm{Cn} \tag{4}$$

Assuming that the annual cash flows are constant within the timeframe of the study, we can get the following expression for the NPV:

$$\begin{aligned} NPV_n^p &= CF_{n,0}^p + \frac{CF_n^p}{(1+k)} + \frac{CF_n^p}{(1+k)^2} + \cdots + \frac{CF_n^p}{(1+k)^{25}} \\ &= CF_{n,0}^p + CF_n^p \left(\frac{1}{(1+k)} + \frac{1}{(1+k)^2} + \cdots + \frac{1}{(1+k)^{25}} \right) = \end{aligned}$$

$$= -I_i^p + \left(\left(\sum_{h=1}^{8760} R_{n,h}^p \right) - OPEX_{n,y}^p \right) \left(\frac{1}{(1+k)} + \frac{1}{(1+k)^2} + \cdots + \frac{1}{(1+k)^{25}} \right) \\ =$$

$$\begin{aligned} &= -I_i^p + \left(\left(\sum_{h=1}^{8760} \Delta E_{n,h}^p \cdot P_h \right) - 0.02 \cdot I_i^p \right) \cdot (\varnothing) \\ &= -p\ I_i^1 + \left(\left(\sum_{h=1}^{8760} P_h \cdot q_{n,h}^p \cdot p \cdot E_{i,h}^1 \right) - 0.02 \cdot p \cdot I_i^1 \right) \cdot (\varnothing) \\ &= p \left[\left(\left(\sum_{h=1}^{8760} P_h \cdot\ q_{n,h}^p \cdot\ E_{i,h}^1 \right) - 0.02 \cdot I_i^1 \right) - I_i^1 \right] \cdot (\varnothing) \end{aligned} \tag{5}$$

where P_h is the price of electricity in the wholesale market in hour *h*, *k* is the financial discount rate, and$(\varnothing) = \frac{1}{(1+k)} + \frac{1}{(1+k)^2} + \ldots + \frac{1}{(1+k)^{25}}$(for the sake of simplicity). For its part, $\Delta E_{n,h}^p$ is the effective energy provided by the *p*-MW PV plant in hour *h*. This effective energy can be express as $\Delta E_{n,h}^p = q_{n,h}^p \cdot E_{i,h}^p$, where $q_{n,h}^p$ represents the percentage of $E_{i,h}^p$ used in the hybrid plant *n* in hour *h*. This percentage will be less than 1 if the sum of the energy generated by the wind facility plus the one generated by the *p*-MW PV plant is greater than the grid capacity of the wind facility (C_j) –case 4.a–, and equal to 1 if this sum is less than or equal to C_j –case 4.b. Note also that the PV system is scalable, this is, $I_i^p = pI_i^1 = 500,000p$ and $E_{i,h}^p = pE_{i,h}^1$.

$$\begin{aligned} \frac{NPV_n^p}{I_i^p} &= \frac{p \left[\left(\left(\sum_{h=1}^{8760} P_h \cdot q_{n,h}^p \cdot E_{i,h}^1 \right) - 0.02 \cdot I_i^1 \right) \cdot (\varnothing) - I_i^1 \right]}{p\ I_i^1} \\ &= \frac{\left(\left(\sum_{h=1}^{8760} P_h \cdot q_{n,h}^p \cdot E_{i,h}^1 \right) - 0.02 \cdot I_i^1 \right) \cdot (\varnothing)}{I_i^1} - 1 \end{aligned} \tag{6}$$

$\frac{NPV_n^p}{I_i^p}$ is a function that has a flat maximum zone that goes from p = 0.1 to that p in which $q_{n,h}^p$ starts having values less than 1.

$$\begin{aligned} DPB_n^p :\ & p\ I_i^1 \\ &= \left(\left(\sum_{h=1}^{8760} P_h q_{n,h}^p p \cdot E_{i,h}^1 \right) - 0.02 \cdot p \cdot I_i^1 \right) \left(\frac{1}{1+k} + \ldots + \frac{1}{1+k^{PBD}} \right) \end{aligned}$$

$$I_i^1 = \left(\left(\sum_{h=1}^{8760} P_h q_{n,h}^p E_{i,h}^1 \right) - 0.02 \cdot I_i^1 \right) \left(\frac{1}{(1+k)} + \ldots + \frac{1}{(1+k)^{PBD}} \right) \tag{7}$$

DPB_n^p has a zone of minimums (not a single minimum point). When $q_{n,h}^p$ begins to show values less than 1 (as p increases), the $CF_{n,y}$ begin to decrease and the DPB_n^p increases.

$$\begin{aligned} IRR_n^p :\ & p\ I_i^1 \\ &= \left(\left(\sum_{h=1}^{8760} P_h \cdot q_{n,h}^p \cdot p \cdot E_{i,h}^1 \right) - 0.02 \cdot p \cdot I_i^1 \right) \left(\frac{1}{(1+IRR)} + \frac{1}{(1+IRR)^2} + \ldots \right. \\ &\quad \left. + \frac{1}{(1+IRR)^{25}} \right) \end{aligned}$$

$$\begin{aligned} I_i^1 = & \left(\left(\sum_{h=1}^{8760} P_h \cdot q_{n,h}^p E_{i,h}^1 \right) - 0.02 \cdot I_i^1 \right) \left(\frac{1}{(1+IRR)} + \frac{1}{(1+IRR)^2} + \ldots \right. \\ & \left. + \frac{1}{(1+IRR)^{25}} \right) \end{aligned} \tag{8}$$

With the IRR_n^p something similar happens to that with $\frac{NPV_n^p}{I_i^p}$. It has an initial maximum zone and when $q_{n,h}^p$ begins to show values less than 1 (as *p* increases), the $CF_{n,y}$ begin to decrease and the IRR_n^p decreases.

Note that *p* affects NPV directly and through $q_{n,h}^p$, which has a negative relationship to *p*; this is, given the energy generated by the wind facility ($W_{j,h}$) and its grid capacity (C_j), the higher *p* is, the smaller the proportion of the PV energy that can be effectively used ($q_{n,h}^p$). Note also that the NPV per € invested, the DPB and the IRR indicator do not depend directly on *p*, although they do so through $q_{n,h}^p = \Delta E_{n,h}^p / E_{n,h}^p$. According to equations (6), (7) and (8), these indexes have a constant maximum value on *p* (minimum in case of DPB) while $q_{n,h}^p = 1$ and when $q_{n,h}^p$ starts decreasing with *p*, they start decreasing as well (because *p* is too high and thus part of the solar energy is not used, falling $q_{n,h}^p$).

The optimal power of the PV plant in each hybrid facility will be the one that allows optimizing the reference financial indicator: NPV, NPV per € invested or DPB (discounted payback period). The IRR index is not considered in the optimization process due to its relatively similar behavior to the NPV/I_0 indicator. Specifically, to find the optimal *p* for each financial index, different values are simulated for each hybrid plant, ranging from $p = 0.1$ to C_n MW, with steps of 0.1 MW.

Multilevel regression model on the determinants of wind energy production

To conclude our empirical analysis, a linear mixed model estimation of wind power generation in the year 2021 is proposed using the sample of wind power facilities. Linear mixed or multilevel models are models containing both fixed effects and random effects. They are a generalization of linear regression models which allows for the inclusion of random deviations other than those associated with the overall error term of the model –on multilevel analysis, see for example Cameron *et al* [14]. They have been used in a wide range of domains, such as education, medicine, labor market, etc., but their presence in studies on the behavior of the electricity markets is scarce at present –see, for example, García-Martos et al. [20], Koen et al. [26], Tso and Guan [51] and Borchers et al. [12].

After trying several specifications, we propose a two-level model of the hourly wind generation. The first level corresponds to the hourly observations (h = 1,…,8760 per wind facility) and the second level to the wind facilities of the sample (j = 1,…,62). When hourly observations are nested in their respective producers, it is admitted that hours of the same firm tend to be more alike than hours chosen at random from the population. Different reasons may explain the specificity of a wind firm: geographic location, network capacity, power grid problems, level of capital, OPEX and CAPEX, ownership, etc.; this model allows control of this kind of unobservable heterogeneity. The proposed model is as follows:

Level 1 model:

Table 2
Statistical description of the main results.

	Variable	Obs.	Mean	Std. Dev.	Min	p25	Median	p75	Max
Financial information	Optimal NPV/I_0	62 units	1.89	0.32	0.91	1.76	1.92	2.22	2.28
	Optimal NPV	62 units	23,500,000	15,000,000	1,656,677	13,200,000	21,100,000	28,900,000	89,100,000
	Optimal discounted payback (DPB)	62 units	4.85	0.76	4.11	4.20	4.70	5.03	8.03
	Optimal internal rate of return	62 units	25.6	2.9	16.6	24.4	25.9	28.6	29.1
Operational information	Optimal PV power in terms of NPV/I_0 (MWp)	62 units	2.28	5.13	0.1	0.3	0.8	2.3	37.3
	Optimal PV power in terms of NPV (MWp)	62 units	27.39	17.11	1.7	16.0	23.9	37.3	99.0
	Optimal PV power in terms of DPB (MWp)	62 units	4.23	6.09	0.2	0.9	1.9	5.0	37.3
	Ratio 'optimal PV power (NPV/I_0)/Wind farm power'	62 units	0.08	0.15	0.003	0.02	0.04	0.10	1
	Ratio 'optimal PV power (NPV)/ Wind farm power'	62 units	1.00	0.00	1.00	1.0	1	1	1
	Ratio 'optimal PV power (DPB)/ Wind farm power'	62 units	0.15	0.17	0.010	0.05	0.11	0.2	1
	(*) Total PV production	62 units × hours of sun	0.66	1.64	0.00	0.07	0.17	0.60	20.4
	(*) Marginal PV production	62 units × hours of sun	0.65	1.64	0.00	0.07	0.17	0.60	20.4
	(*) Marginal PV production/Gap production	62 units × hours of sun	0.04	0.08	0.00	0.00	0.01	0.04	1.0
	(*) q = Marginal PV production/ Total PV production	62 units × hours of sun	0.99	0.01	0.06	1.0	1.0	1.0	1.0

(*) At the optimal PV power (MWp) in terms of NPV/I0.

$$\begin{aligned} WF_{hj} =& \beta_{0j} + \beta_{1j}E^1_{hj} + \beta_{2j}C_j + \left(\beta_{3,2}\cdots\beta_{3,12}\right)\left(D_{February}\cdots D_{December}\right) \\ &+ \left(\beta_{4,2}\cdots\beta_{4,24}\right)\left(D_{hour2}\cdots D_{hour24}\right) + u_{hj} \end{aligned} \tag{9}$$

with u_{hj}*iid* $\sim\ N(0,\sigma_u^2)$ *for* $j = 1,\cdots,62;\ h = 1,\ \ldots,8760;$ h = 1, …,8760.

Level 2 model (specific wind facility effect):

$$\beta_{0j} = \gamma_{00} + v_{0j};\ \ \beta_{1j} = \gamma_{01} + v_{1j};\ \ \beta_{2j} = \gamma_{02} + v_{2j} \tag{10}$$

$$where\ \ v_{0j}iid \sim\ N(0,\sigma^2_{v_0}), v_{1j}iid \sim\ N\left(0,\sigma^2_{v_1}\right), v_{2j}iid \sim\ N\left(0,\sigma^2_{v_2}\right),$$

$$cov\left(v_{0j},u_{hj}\right) = cov\left(v_{1j},u_{hj}\right) = cov\left(v_{2j},u_{hj}\right) = 0,$$

$$cov\left(v_{1j},v_{0j}\right) = cov\left(v_{2j},v_{0j}\right) = cov\left(v_{1j},v_{2j}\right) = 0\quad forj = 1,\cdots,62;h = 1,\cdots,8760$$

Integrating both models:

$$\begin{aligned} WF_{hj} =& \gamma_{00} + \left(\gamma_{01} + v_{1j}\right)E^1_{hj} + \left(\gamma_{02} + v_{2j}\right)C_j \\ &+ \left(\beta_{3,2}\cdots\beta_{3,12}\right)\left(D_{February}\cdots D_{December}\right) \\ &+ \left(\beta_{4,2}\cdots\beta_{4,24}\right)\left(D_{hour\,2}\cdots D_{hour\,24}\right) + v_{0j} + u_{hj} \end{aligned} \tag{11}$$

The response variable is the hourly generation of each wind facility WF_{hj}. The fixed part of the model is composed of the global average wind production for all the hours (γ_{00}) plus the PV energy production E^1_{hj}, which acts as a proxy for the irradiation of the province where the wind generator is located, plus the capacity of the wind facility C_j, plus the dummy variables which control for the month of the year {$D_{February}$, …,$D_{December}$} and the hour of the day with sun {D_{hour7}, ⋯, D_{hour21}} –dummies $D_{January}$ and D_{hour6} are omitted from the estimate in order to avoid multicollinearity (hour 6 is the first hour of the day with some PV production during the year 2021 in Spain). The random portion of the mixed model is composed of two parts. On the one hand, the purely random effects v_{0j}, v_{1j} and $, v_{2j}$ respectively measure the specificity (random intercept) of every particular wind facility $\left(v_{0j}\right)$ and the cross-effects that every particular wind facility has on the slopes of the regressors PV generation E^1_{hj} $\left(v_{1j}\right)$ and wind facility capacity C_j $\left(v_{2j}\right)$. On the other hand, the overall or level 1 error term $\left(u_{hj}\right)$ represents disturbances that idiosyncratically affect each observation in the sample. In summary, in the proposed mixed model the average wind production of a specific firm within the year can move away from the global average of the year and, in addition, the way in which solar irradiation (proxied by the PV production) and wind facility capacity affect wind production may differ among the different wind facilities.

The 2-level model must be estimated by using maximum likelihood techniques since it has got a composite error term whose variance is partitioned into the between-firm variance components (the variance of the level 2 residuals) and the between-hour variance component (the variance of the level 1 residual).

Results and discussion

This section describes the main results obtained from the economic analysis of the 62 hybrid plants analysed. In general, there is a significant degree of heterogeneity between the different investment alternatives; heterogeneity that is largely explained by the geographical location of each hybrid plant. Table 2 summarises the main results obtained.

According to this table, we can infer the following insights:

- The optimal NPV for the hybrid units is on average M€ 23.5 for a timeframe of 25 years and a discount rate of 7% (note that there is a plant with a maximum NPV of M€ 89.1 and a plant with a minimum value of M€ 1.6). The investments also have an interesting average NPV per € invested of 1.89 (standard deviation 0.32) and average DPB of 4.85 years (standard deviation 0.76). These figures can pose an interesting scenario for investors.
- In terms of NPV, the optimal value of PV power to install would be C_n (average value $p = 27.4$), giving rise to a 'PV power/Wind power' ratio of 1 (100%). In other words, it is interesting to install all the PV capacity that the grid itself allows for the corresponding wind facility. This occurs because, even if the size of the PV plant is increased up to C_n, all or almost all the PV energy ends up being useful and, therefore, profitable –in fact, it would even be interesting (in economic terms) to install a PV power greater than C_n if the Spanish regulation allows it; at least up to a certain level of p.

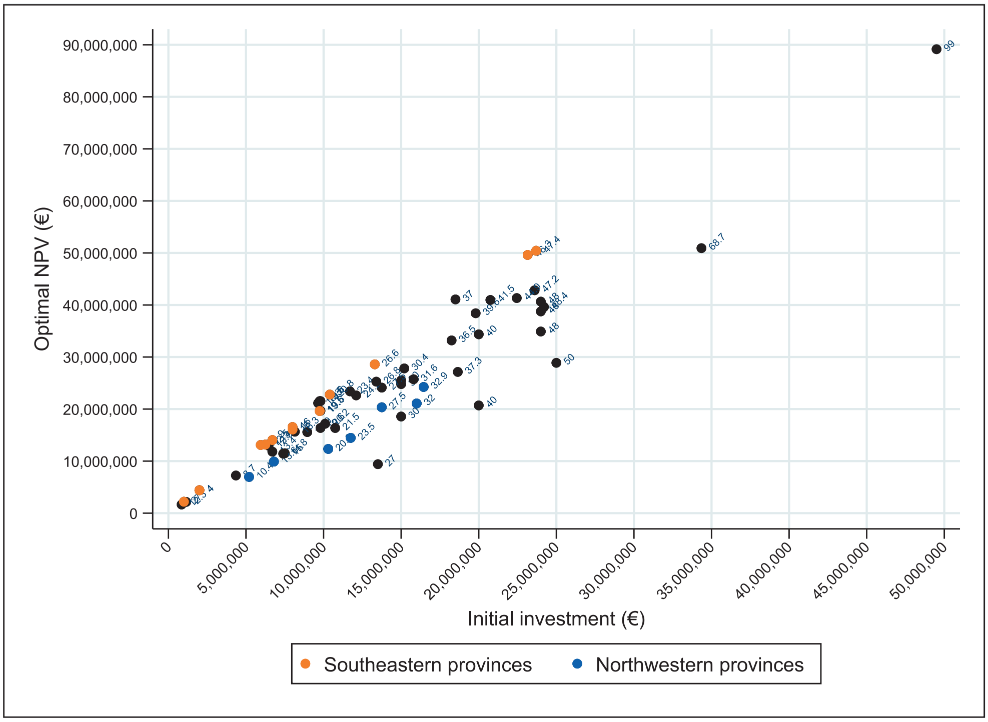


Fig. 4. Optimal NPV vs. Initial investment of a PV plant.

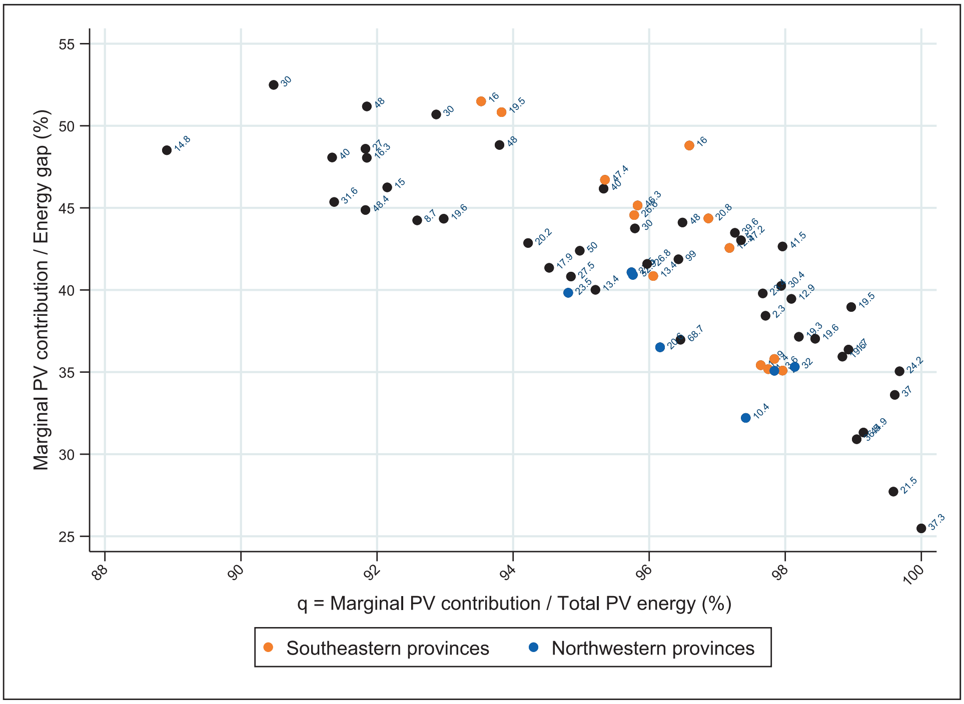
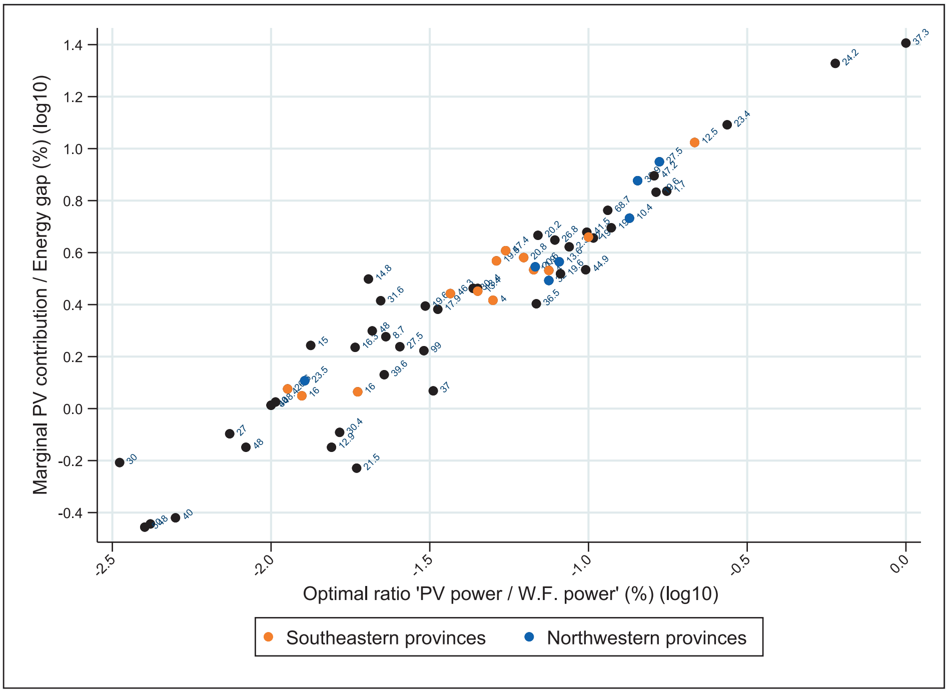
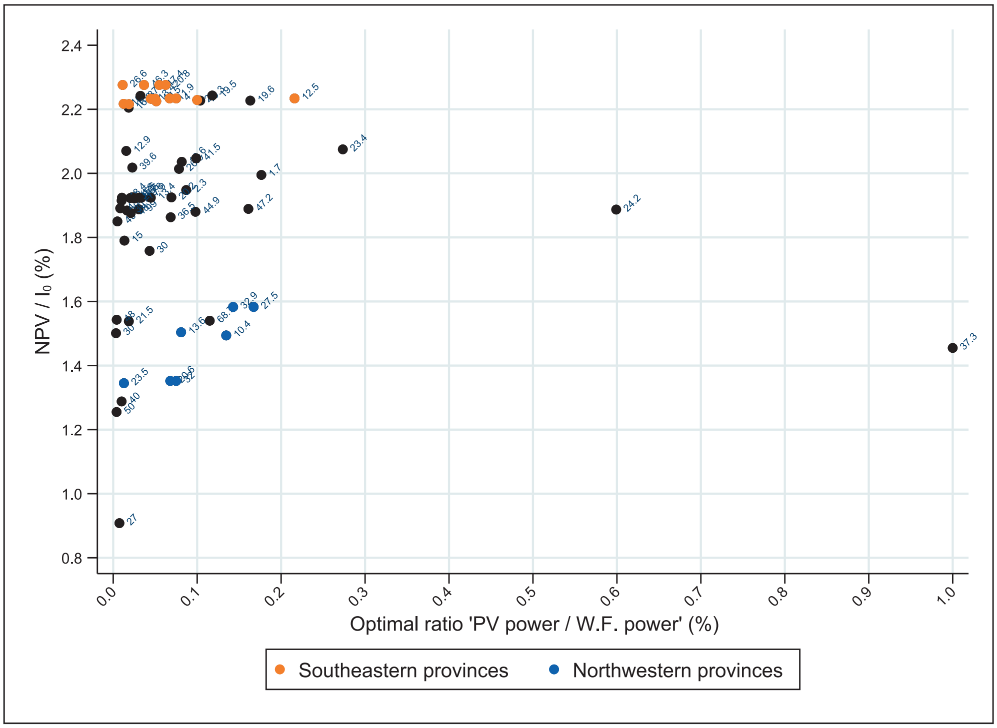


Fig. 5. 'PV marginal contribution/Wind energy gap' vs. $q^{p}_{n,h}$ (optimal p in terms of NPV).

- The reasoning on the optimal PV power to be installed changes if the investment is analysed from the point of view of NPV per € invested. In this case, the optimal value of the PV power would be (on average) 8% of the wind power already installed (standard deviation 15%) –average PV power $p = 2.3$. With these peak powers, lower than those corresponding to the NPV indicator, the marginal PV production ($\Delta E^{p}_{n,h}$) has an average value of 0.65 MWh (standard deviation 1.64 MWh). This marginal contribution represents, on average, 4% of the wind production gap and 99% of the PV production ($E^{p}_{i,h}$) –these percentages would be 41.25% and 95.9%, respectively, if the installed peak power were C_n, the optimal one from the point of view of the NPV.
- The IRR index, with an average value of 25.6%, yields a promising result. It suggests that a photovoltaic power greater than 8% of wind power may be installed as long as the return obtained on the investment is greater than the weighted average cost of capital.



(a) ‘PV marginal contribution / Wind energy gap’ vs. optimal ratio of PV/Wind powers



(b) NPV/I_0 vs. optimal ratio of PV/Wind powers

Fig. 6. Optimal ratio of PV/Wind powers.

The extensive battery of parameters and indicators obtained for each possible investment allows for a rich graphical analysis. Thus, Fig. 4 shows that there is a strong positive correlation between the NPV and the initial investment –point labels are C_n. Remember that the initial investment depends proportionally on the optimal PV power of the plant: $I_i^p = 500,000p$. Note also that the slope of the origin-point line of each point in Fig. 4 measures the NPV/I_0 of the corresponding hybrid plant. In the graphical analysis, it is proposed to compare two very different geographical locations within the Spanish territory: the provinces of southeastern Spain (Almería and Granada) and northwestern Spain (Lugo, Pontevedra and A Coruña) where wind facilities have been identified. It is observed that Southeastern provinces show better results than northwestern provinces for any given level of investment; moreover, the differences increase when the amount invested is greater. It

Table 3
Linear mixed (2-level) model of the wind generation.

	Mixed-effects ML regression			Number of obs. = 289,257			
	Group variable: wind farm			Number of groups = 62			
	Log likelihood = –1031102.6			Wald chi2(28) = 12402.02; Prob > chi2 = 0.000			
		Coefficient	**Std. err.**	**z**	**P > z**	**[95% Conf. Interval]**	
	PV production	−3.58***	0.646	−5.54	0.000	−4.841	−2.309
	WF capacity	0.31***	0.022	13.74	0.000	0.261	0.348
Reference month: January	February	1.45***	0.099	14.71	0.000	1.261	1.648
	March	0.20*	0.116	1.71	0.087	−0.029	0.425
	April	−1.93***	0.116	−16.58	0.000	−2.156	−1.7
	May	−1.63***	0.122	−13.37	0.000	−1.871	−1.393
	June	−2.90***	0.13	−22.27	0.000	−3.156	−2.646
	July	−2.72***	0.135	−20.05	0.000	−2.981	−2.45
	August	−3.76***	0.132	−28.45	0.000	−4.017	−3.499
	September	−4.69***	0.12	−38.91	0.000	−4.922	−4.45
	October	−4.05***	0.101	−40.23	0.000	−4.246	−3.852
	November	−1.39***	0.089	−15.7	0.000	−1.564	−1.216
	December	−1.93***	0.087	−22.02	0.000	−2.097	−1.754
Reference hour of day: 6:00 am	Hour 7	−0.23	0.203	−1.12	0.263	−0.626	0.171
	Hour 8	−1.14***	0.204	−5.59	0.000	−1.54	−0.741
	Hour 9	−0.87***	0.231	−3.78	0.000	−1.324	−0.42
	Hour 10	−0.52*	0.282	−1.84	0.066	−1.071	0.035
	Hour 11	−0.2	0.333	−0.59	0.552	−0.85	0.454
	Hour 12	0.02	0.371	0.06	0.949	−0.703	0.751
	Hour 13	0.28	0.391	0.71	0.480	−0.49	1.043
	Hour 14	0.48	0.391	1.23	0.217	−0.284	1.25
	Hour 15	0.44	0.371	1.2	0.230	−0.282	1.172
	Hour 16	0.22	0.333	0.65	0.517	−0.437	0.867
	Hour 17	−0.09	0.282	−0.32	0.746	−0.645	0.461
	Hour 18	−0.36	0.231	−1.54	0.124	−0.809	0.097
	Hour 19	−0.3	0.204	−1.48	0.139	−0.701	0.098
	Hour 20	0.14	0.201	0.72	0.471	−0.249	0.538
	Hour 21	0.38*	0.219	1.73	0.084	−0.051	0.807
	Constant	2.21***	0.3	7.35	0.000	1.618	2.796
Random-effects		Estimate	Std. err.			[95% Conf. Interval]	
	Wind farm (level 2)						
	var(v_{1j})	7.32***	1.381			5.055	10.592
	var(v_{2j})	0.02***	0.004			0.014	0.028
	var(v_{0j})	0.00	0.00			0.00	0.00
	var(u_{hj}) (level 1)	72.9***	0.192			72.549	73.301

LR test vs. linear model: chi2(3) = 63999.58; Prob > chi2 = 0.0000.
Significant levels: * p <.1; ** p <.05; *** p <.01.

seems clear that the combination of installed powers, wind, and sun is more favorable in the southern regions.

Fig. 5 shows a non-linear negative relationship between the percentage of the wind gap production (between C_j and $W_{j,h}$) covered by the marginal PV energy ($\Delta E^{p}_{n,h}$) and the percentage $q^{p}_{n,h} = \Delta E^{p}_{n,h}/E^{p}_{n,h}$ –optimal *p* in terms of NPV. A value of this[1] last percentage of 100% ($q^{p}_{n,h} = 1$) would mean that the solar energy produced ($E^{p}_{n,h}$) would always be under the wind gap production, so that all the solar energy is used and profitable. Observe that the slope of the origin-point line of each point in Fig. 5 measures the ratio ‘Total PV energy/Wind energy gap’ of the corresponding hybrid plant; the flatter this slope, the smaller the percentage of the gap that represents the PV production.

Fig. 6(a) and 6(b) take as a reference the ‘NPV per € invested’ indicator (point labels represent C_n in both figures). Fig. 6(a) indicates that those hybrid units with a higher ratio ‘PV/Wind powers’ (optimal *p* in terms of NPV/I_0) cover a greater percentage of the wind production gap with their PV energy; remember that the average value of this coverage is 4% (see Table 2) –in this figure, the variables have been represented in log base 10 to show more clearly the behaviour of the units closest to the origin–. For its part, Fig. 6(b) directly relates the NPV/I_0 indicator to the mentioned ratio ‘PV/Wind powers’; the figure shows that Southeastern provinces give better results than the Northwestern provinces independently of the selected ratio.

Our empirical analysis ends with the estimation of the mixed model on wind farm generation contained in equations (9), (10) and (11) –see Table 3–. To measure the pure effect of the PV production (irradiation) on wind generation, the estimation uses only the sun hours (in which there is PV generation). Examining the estimation results of the fixed portion of the model, it is observed that the coefficient of PV production is negative and significant, i.e. each MWh of additional PV production is accompanied by an average reduction in wind energy production of 3.58 MWh. Therefore, it appears that the relationship between wind and sun is not that of two independent random variables. For its part, the capacity of the wind facility has a positive average effect on the wind generation, although the coefficient is less than unity (0.31), which means that one more MW of capacity does not imply that wind energy production will increase by 1 MWh.

As for the dummy variables, almost all the coefficients of the month dummy variables are significant at the 99% confidence level, being the first months of the year those that imply a greater wind energy production (plausible result in the Spanish case). Note that January is the reference category, and that only February and March cause a greater positive effect on the overall constant of the model. The coefficients of the hourly dummies are generally insignificant, which is possibly due to the different hourly patterns shown by the wind in the different wind facilities considered.

The random part of the model allows us to estimate the three between-firm variance components (v_{0j}, v_{1j}, v_{2j}) and the between-hour variance component (u_{hj}). In the estimation, most of the variance in the dependent variable is due to noise, although it is also true that the variance of the firm effect on the wind-sun relationship is not negligible ($var(v_{1j}) = 7.31$) and is much greater than the variance of the rest of the level 2 random effects –this variance means that the standard deviation of the random slope v_{1j} that measures the cross-effect that every

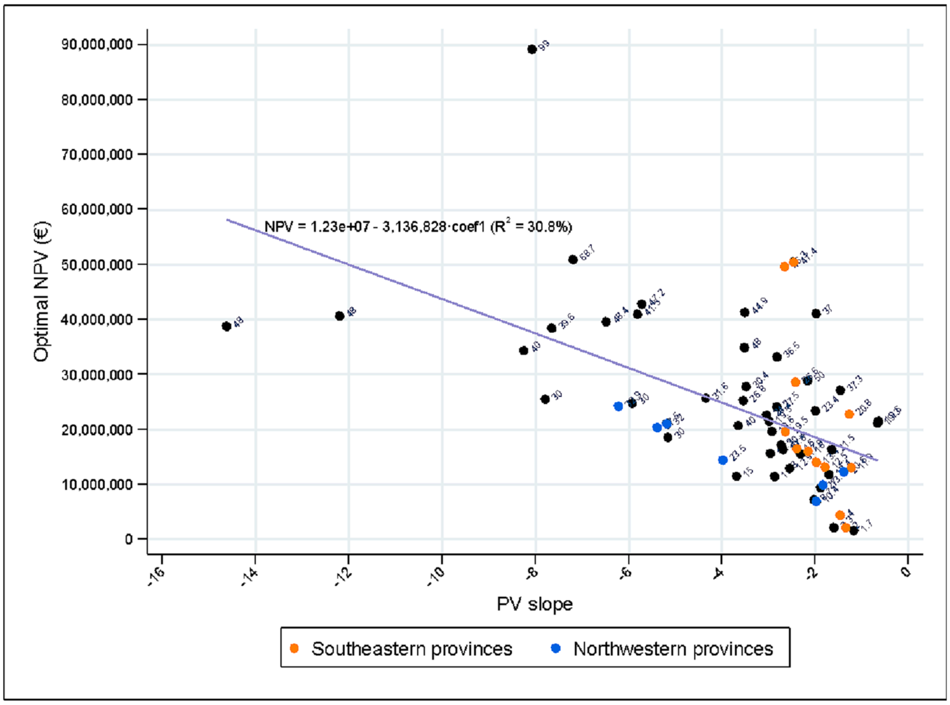


Fig. 7. The relationship between NPV and the slope of the PV production regressor.

particular wind facility has on the slope of the PV production regressor is 2.7 MWh, not at all inconsiderable. Given this result, it may be interesting to relate the full coefficient of the PV production ($\gamma_{01} + \nu_{1j}$) to the NPV obtained by the different hybrid units when operating with an optimal photovoltaic configuration; Fig. 7 shows this relationship. As expected, a negative relationship between the financial index and the estimated parameter is observed; that is, approximately ($R^2 = 30.8\%$), when the slope becomes one point more negative, the NPV of the investment improves by more than €3 million. This result determines that hybridization should require previous studies of the climatic conditions of the area in which the investment is to be carried out (using for that historical series of irradiation and wind).

Conclusions

The main objective of this research is to determine the optimal sizing of a photovoltaic plant that is going to be installed within an existing wind power facility. Given the hourly electricity generated throughout the year by the wind farm and its grid capacity, the optimal power of the PV plant (in the hybrid installation) will be the one that maximises the return on the investment in PV generation. The PV power of the plant will be adjusted so that the sum of PV and wind energy generation converges to the maximum nominal power that the grid can allow. The empirical analysis is based on the geographical location and the installed power of 62 wind facilities in Spain in the year 2021. In addition to the financial analysis, we have estimated a multilevel regression model for the hourly wind production; the model assumes that two hours of wind generation from the same firm are more similar to each other than two hours of wind generation chosen at random from the population.

The results show the economic feasibility of installing a photovoltaic plant coupled with a wind installation. The optimal sizing (peak power) of the PV plant represents, on average, 8% of the capacity of the wind facility if the reference indicator is the NPV (Net Present Value) per € invested, while this percentage rises to 100% if the NPV is taken as a reference. Another issue to consider when evaluating the business is the geographical location of the wind facility, since the complementarity between sun and wind can differ considerably between the different regions (even within the Spanish territory).

The multilevel model on wind generation shows that the coefficient of PV production is negative and significant; thus, each MWh of additional PV production is accompanied by an average reduction in wind energy production of 3.58 MWh –it therefore appears that the relationship between wind and sun is not that of two independent random variables. Moreover, the capacity of the wind facility has a positive average effect on the wind generation, although the coefficient is less than unity (0.31), which means that one more MW of capacity does not imply that wind energy production will increase by 1 MWh.

We hope that the findings of our study will help in the design of hybrid plants, even though future calculations would have to be carried out to fine-tune the sizing of the PV plant. For future research, it would be interesting to extend the sample to wind facilities located in other regions or countries and to calculate the optimal size of a hybrid wind/photovoltaic plant taking into account other complementary criteria (economic, technical, social, etc.) and the existence of energy storage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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