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ScienceDirect

Energy Procedia 157 (2019) 1144–1163

Energy Procedia

www.elsevier.com/locate/procedia

Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES18, 19–21 September 2018, Athens, Greece

Wind energy planning for a sustainable transition to a decarbonized generation scenario based on the opportunity cost of the wind energy: Spanish Iberian Peninsula as case study

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Abstract

Most countries in Europe are going under a significant transformation process from carbonized power energy sources to renewable and sustainable ones to feed their increasing demands. European Union targets on its energy roadmap states that by 2030, a reduction of 40% of CO_2 emissions regarding the 1990 levels must be done and full transition must be completed by 2050. Thus, EU member countries, such Spain, are carrying out lots of investments to transform their power generation structure by promoting the installation of renewable energy power plants, with a significant visual and environmental impact. In the case of Spain, it is planned that, by 2030, 27% of final power consumption must be renewable, with approximately 31 GW of installed wind energy (8 GW must be installed in the next 10 years). Wind energy is supposed to be one of the generation leaders in this transformation context due to its high performance, high availability and fast decreasing costs.

Nevertheless, wind farms have been installed on-shore with great success since the decade of the 90s covering the locations with the best wind resource. Thus, many of the installed wind turbines have overcome the half part of their expected lifespan and their payback periods, but the learning curve of the wind energy technology has improved exponentially since then. This paper is focused on the true valorization of an existing wind farm and the efficacy of the exploitation of the site's wind resource. A novel repowering decision support model based on the opportunity cost analysis between repowering the current wind farm with the latter technologies and full depletion of the wind farm is proposed and applied to the Spanish Iberian Peninsula case study. Results show that the repowering option is significantly attractive in most cases and its proper application could have, not only a positive environmental effect, but also an economic impact on the sustainability of this source of energy.

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Selection and peer-review under responsibility of the scientific committee of Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES18.
10.1016/j.egypro.2018.11.282

Keywords: Energy Planning; Wind Energy; Repowering; Opportunity Cost; Wind Resource Valorization.

1. Introduction

The European Union (EU) states on its energy roadmap for 2050 that EU members have to prepare their infrastructure for further decarbonisation of its energy system in the longer term towards 2050. This framework should, therefore, also be able to accommodate possible future EU energy and climate policy objectives [1], being aligned with the goal of promoting the large-scale use of renewable energy sources, but always considering minimum cost and maximum efficacy criteria. Thus, most EU members have been carrying out energy policies according to the 2050 roadmap since several years ago, with different success rates depending on the economic and financial circumstances. European Directives on economy decarbonisation [1] are being transposed gradually into national regulations in the EU members. In particular, in Spain, Law 54/1997, of the Electricity Sector [2], although partially updated by Law 17/2007 and Law 24/2013 and several Royal Decrees, is still in force and promotes the establishment of a stable regulatory framework which aims the reduction of electricity prices, based on the free competition of different power generation technologies.

With the aim to reduce at least 40% of the CO_2 emissions in comparison with the 1990 levels in the energy sector, the renewable energy sources (RES) must be highly promoted. In this sense, the wind energy has demonstrated to be one of the most mature and profitable technologies in this field, as this technology has been exponentially evolving since more than 40 years at industrial level if we consider the modern integration of these generators in the power grid and more than 140 years if we consider their true origins (actually, one of the first power wind mill was developed by Charles F. Brush in 1888). Due to the characteristics of this technology (maturity and reliability) and the national regulations promotion, wind energy installed capacity is rising exponentially in many countries, e.g. in Spain wind capacity will significantly increase in the next 10 years reaching the 31 GW according to current forecasts [3]. Repowering helps to meet the objectives set by Europe in relation to RES penetration for the 2030 and 2050 energy supply scenarios [3], [4].

Wind mills generators, also known as wind turbines, are relatively complex devices which the International Electrotechnical Commission (IEC), through the IEC-61400 standard [5], instructs that the design lifetime can be considered for at least 20 years. Moreover, this life span can be increased by the application of modern life extension techniques, which are associated with extra maintenance costs [6], [7]. Numerous published studies, such as [6]–[8], and the mere existence of older wind farms (WFs) in many national WFs stock, show that, if the maintenance actions are applied properly, is not hard to find working WF close to, or even over, 20 years. However, it should be considered the fast growing learning curve of this technology, which makes older wind turbines significantly less efficient and onerous than modern ones. The development of a wind turbine generator (WTG) has undergone a major technical renovation in the last 15 years thanks to the global competitiveness of manufacturers. Current standards have increased significantly, both qualitative and quantitative in the recent years and this trend, far from being stabilize, is continuously increasing. Thus, at some point, the option of replacing the working WF arise between investors and energy planners. We wonder where is the maximum profitability, both for the system and for investors? Are we exploiting an important wind resource at maximum efficacy? Do we really need to build new WF, with their associated environmental impacts, or do we only need to update our stock? This is not a trivial decision and must be taken with care as it relies on dynamic management benefits [9], [10].

The repowering of WFs is a trend that is taking increasing interest among the scientific and engineering community, as many studies show [9] [10], [4] [16], [18]. The cause of this interest is fully justified if we observe the accumulation of WFs older than 15 years in pioneering countries installing this technology, such as Spain.

Although many particular studies have demonstrated the potential benefits (including a significant reduction of the electricity price in the spot market) of repowering WFs in Spain, even considering scenarios of decrease or cancellation of premiums for the production of electricity [10], repowering has not been implemented actively.

The main goals of this paper are, first, to conduct a deep analysis of the involved costs of repowering a WF, focusing on the true valorization of the existing WF and the efficacy of the exploitation of the site's wind resource, and secondly, to develop a decision support model based on the opportunity cost analysis between repowering an existing WF and a full depletion. As case study, this model is applied to the Spanish Iberian Peninsula case, where although some authors have carried out some studies (concluding that repowering a WF can be profitable after 15 years of operation [14]), but usually considering very particular circumstances (extreme old WTGs and very high wind resource). The generalized application of the developed model will help energy planners to prioritize inversion decisions and optimize energy incentives.

This paper is structured in 4 sections. The introduction includes a brief introduction to the repowering concept for novel readers and an overview of the development of the wind energy in Spain. Next section describes the involved costs of a WF included in the repowering analysis and describes the fundamentals of the developed decision tool. Section 3 shows the obtained results of the simulation in the case study, which are also discussed. Finally, section 4 summarizes the main conclusions of the study.

Nomenclature

CAPEX	capital expenditures
CF	cash flow
EU	European Union
FIT	feed-in-tariff
IEC	International Electrotechnical Commission
IRR	internal rate of return
NPV	net present value
OC	opportunity cost
O&M	operation and maintenance
OPEX	operational expenditures
r	discount rate
RES	renewable energy sources
RV	residual value
WF	wind farm
WTG	wind turbine generator

1.1. Brief introduction to the Repowering

The repowering of a WF can be defined roughly as the engineering process of replacing existing WTGs in an existing WF, usually in operation, with new WTG. The new installed WTG can either offer a larger capacity or more efficiency than replaced, implying a net increase in the generated energy [9], [15]. The repowering can be conducted either when the operating WTGs have reached their useful lifetime (which is the more extended practice) or earlier. This process involves a significant update of the facilities in order to extend their useful lifespan, performance and, sometimes, also increase the power capacity [9].

The need of repowering arises because, although the base configuration of a modern power generation WTG remains the same since the last 40 years (horizontal hub, three-bladed, windward rotor), WTGs have improved performances and, what is more important in this case, have increased sizes with lower costs. Thus, WTGs have evolved from small generators of 20 kW of nominal power in the 1980s, to giant machines of 8 MW of nominal power nowadays, with strong increases in their yields [12]. As technology improves rapidly, a substantial part of the world fleet has become obsolete. At the end of 2017, 17% of the worldwide installed capacity (93 924 MW) was at least 10 years old and 6% (31 100 MW) was at least 15 years old [16]. This evolution, followed by the inexorable aging of the equipment, means that the first WF are close or have already reached the end of their useful lives and, as they become obsolete or simply ineffective, many investors and energy planners are considering the possibility of repowering them [4]. However, there are still some limitations that prevent the repowering, such as economic, legislative, institutional and financial barriers [14], [17].

Repowering first emerged in California and Denmark during the 1990s. It was followed by a new wave of repowering in the Dutch and German energy markets in the 1990s and the beginnings of the 21st Century [12], [14]. Since then, four countries or regions can be considered the main markets of repowering in the whole world: (i) Denmark, (ii) Germany, (iii) Spain, and (iv) California [18].

Denmark was the first country to promote repowering. The support of public policies for repowering was instituted there in 1994 [14]. The substitution of inefficient WTGs in operation since the end of the 1970s (with a nominal power of 22 kW) was considered necessary [4]. From then on, wind energy showed a strong development and peaked in 2000, with more than 6 200 WTGs installed. On the other hand, in Germany 336 WTGs (with a nominal power of 366 MW) were decommissioned and replaced with 679 MW from 238 brand new WTGs in 2016 [18].

California can be considered the major market for repowering. Just in the 1980s it was installed 1 320 MW of wind energy (out of the 2 230 MW total installed in all USA). However, California had problems developing a robust repowering market due to a variety of regulatory and policy challenges [14] and, thus, by the end of 2007, only 365 MW out of the 1 600 MW of installed wind energy capacity that operated in the 1990s had been repowered [18], [19]. The total repowering until 2007 was equivalent to approximately 20% of the wind power capacity installed in the state in 1994. Moreover, while 245 MW were repowered before 1999, only 23 MW were reactivated between 1999 and 2003 [18].

Authors in the literature use to define three repowering options including (i) full, total or complete repowering, (ii) partial repowering, and (iii) lifetime extension.

- Full repowering refers to the decommission and complete substitution of operative WTG equipment, including tower and foundations parts [11], [20]. With full repowering, part of the existing project infrastructure, such as roads, buildings and interconnection equipment, will be used in the new project. In addition, there is the possibility of offsetting the costs of repowering by recycling or selling older equipment in secondary markets or developing countries [10].
- Partial repowering is referred to the replacement of only a portion of the WTG witch conform the repowered WF combining old WTGs with new WTGs [11].
- Lifetime extension is the lightest form of repowering and, actually, some authors do not consider it as a repowering option. It consists on the substitution only of damaged mechanical assemblies, electrical generators and, sometimes, blades, remaining the existing tower. Some auxiliary components, such as control systems, can also be replaced [20]. This option allows existing projects to be updated with equipments that increase energy production, reduce machine loads, increase capacities and improve the overall project reliability. It is assumed that the performance improvements associated with the lifetime extension, although greater than remaining the initial WTGs, are lower than for a full repowering option [20].

The main advantages of repowering a WF can be listed as:

- As a WTG ages, reliability decreases and the shortage of spare parts increases, which means that operation and maintenance costs also rise [12]. The advance of the technology makes that the most modern WTGs have lower fail rates than older ones, without taking into account their degradation due to aging, reducing the maintenance costs [12], [18]. This results in higher costs for maintenance and reparations, in addition to production losses from turbine downtimes. Ziegler et al. in [8] showed that the business case for lifetime extension is very sensitive to modelling of wear out and failure rates.
- First WF projects were placed in the best available sites, characterized by a better wind resource (higher power density). Then, currently available places for WF use to offer significantly lower power density. Thus, repowering actions help investors to recover better places for WF projects, which directly affects their profitability [12].
- New WTGs are higher, with a larger rotors and can cover larger areas [4]. Replacing older WTGs with newer units help to generate the same (or even increase) power with fewer WTGs units, reducing the environmental impact [9], [11], [12], [17]. Not only lower visual impact is gathered [12], [17], but also lower avian mortality and a lower noise impact can be achieved [17].

- Repowering projects benefit from long-term wind resource data, which reduces uncertainty and helps to select the most appropriate WTG class depending on the wind conditions [12], reducing the risk of the investment [9].
- Repowering, instead of dismantling, preserves local jobs and continues to provide incomes to the municipalities by taxes collection [12].
- Modern WTGs have a much better integration in the power grid and even can help to solve some voltage peaks/sags and/or frequency perturbations on weak grids [12], [17].
- Contributes to the creation of a second-hand WTG market. Older WTGs can be resold in developing countries or to distributed generation investors, helping to establish a cycle-economy [9].
- Repowering helps itself to improve the technology and boost its learning curve [9].

On the other hand, some disadvantages should be highlight:

- If the repowered WF increases its nominal power may need to face extra costs for the grid integration and substation reinforcement [1]. Moreover, sometimes these actions cannot be performed [9].
- If the repowered WF keeps the same nominal power, the project may result less attractive for investors.
- Project promoters may face new complex authorization processes [11]. Because of operational changes, new permissions can be required by the local authorities [9], [12].
- In some countries it can be found logistical problems, such as hub height limitations [20].

Table 1 summarizes the Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis associated with the repowering of a WF which collects previously detailed advantages and disadvantages.

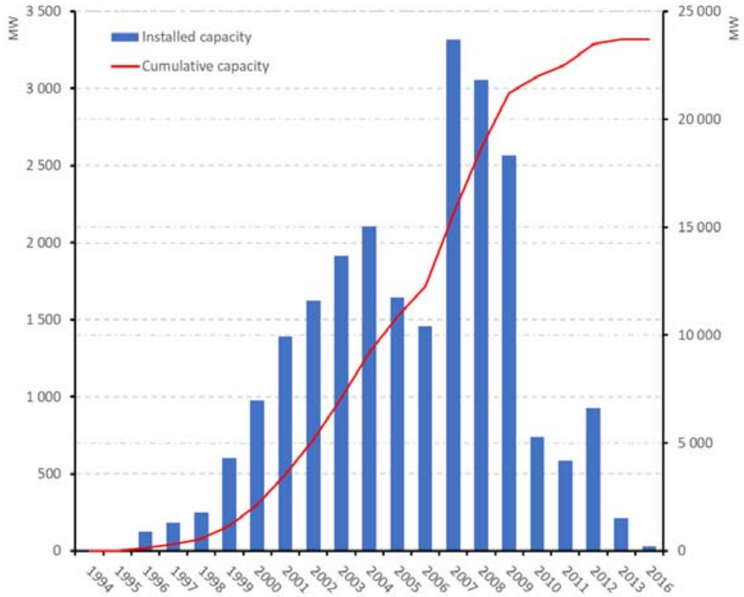
Table 1. SWOT analysis of the repowering of a WF.

Strengths	***Weaknesses***
Advanced technology.	High investment needs.
Lower downtime rates.	Power grid limitations.
Increase of the power generation capacity.	Generation technologies with lower LCOE.
Long-term wind data records.	
Green energy generation.	
Lower project costs.	
Reduction of O&M costs.	
Opportunities	***Threats***
Unlocks higher wind resource sites.	Electricity prices uncertainty.
Compliance with European objectives.	Complex administrative processes.
Jobs creation and incomes from taxes.	Insecurity and instability of the legal framework.
Secondary market for decommissioned WTGs.	

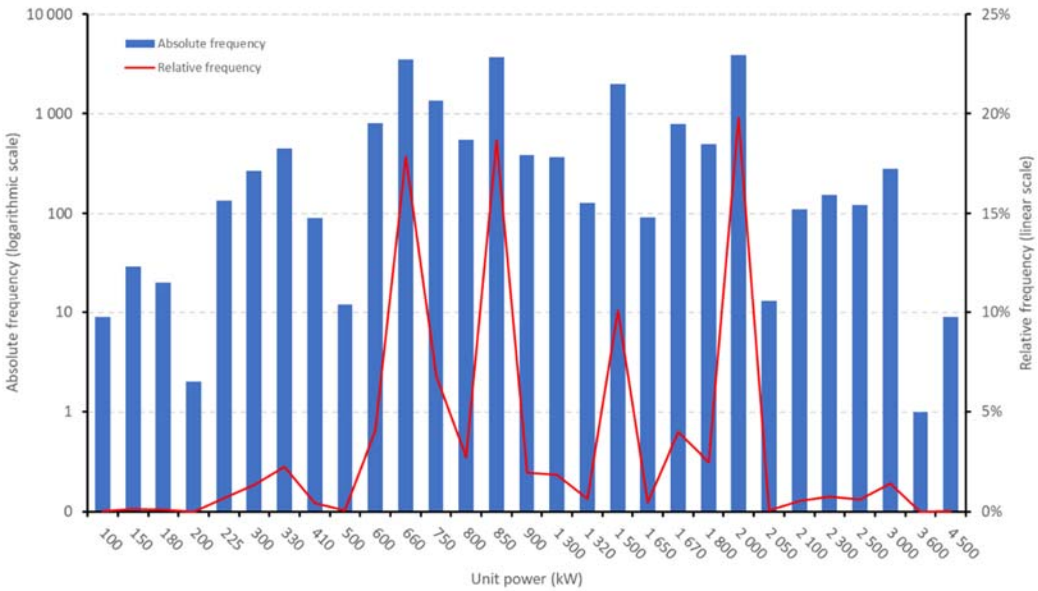
1.2. Wind energy generation overview in Spain

As it can be observed in Fig. 1(a), the Spanish wind system accounts on 23 GW of installed capacity by 2018, corresponding to 19 811 WTGs. This figure also shows clearly that half part of the current installed capacity was installed after 2006 where RES national policies were clearly attractive for investors. An inventory of WFs in Spain has been carried out, based on the data available in [21], and results are shown in Fig. 1(b). In the period since 2004 to 2009 WTGs typical nominal power was in the range from 300 kW to 900 kW. More than the half part of the WTGs stock in Spain has a power less than or equal to 850 kW and typical unit rated power of installed WTGs are 2 MW (20%), 850 kW (18%), and 660 kW (17%). Less than 5% of the Spanish WTG stock has a rated power greater than 2 MW.

Moreover, 30% of the WFs in Spain have a nominal power capacity greater than 30 MW, while approximately 16% of them have a nominal power lower than 5 MW. Furthermore, 57% of installed WTGs have a rated power lower than 1 MW.



(a)



(b)

Fig. 1. (a) Installed and cumulative wind energy capacity installed in Spain. (b) Absolut and relative frequencies distributions of installed WTGs in Spain according to their nominal power (blue bars: absolute frequency, red line: relative frequency).

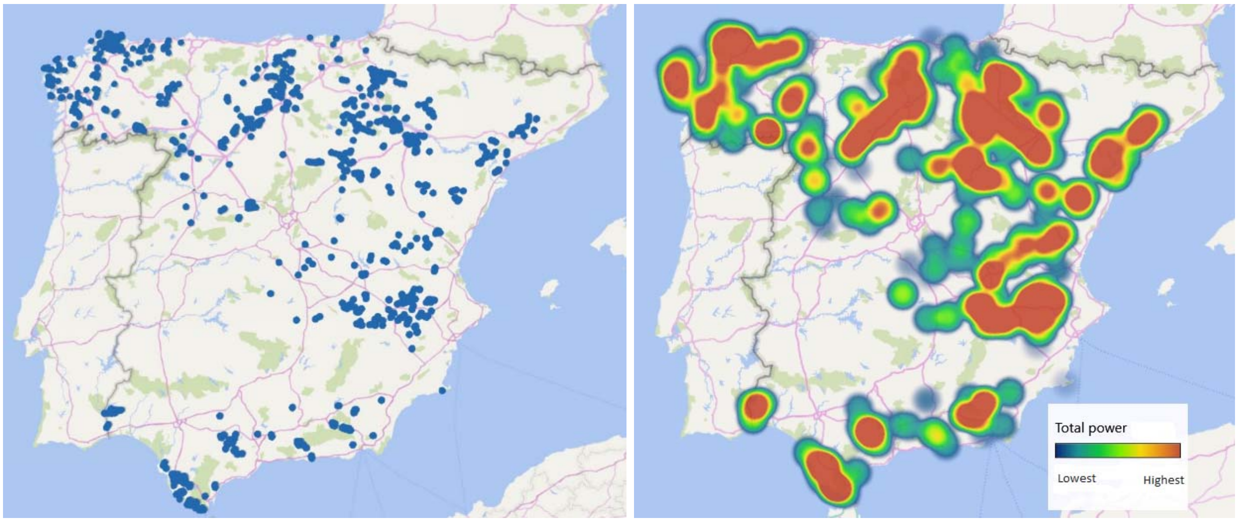
The average age of the WFs in Spain is approximately 12.6 years, which means that have overcome more than the half part of their expected useful lifespan. Moreover, about the 34% of the WFs are over 15 years old, and around 78% are 10 years old or older, representing more than 18,600 MW of the installed capacity (81%).

Table 2 summarizes the most common WTG installed models in Spain and their main characteristics. As it can be observed, most of them were commissioned at the beginnings of the 21st Century, while Gamesa is the manufacturer with a higher deployment. Rotor diameters are 63.1 m on weighted average, and the weighted average unit rate power is 1 197 kW.

Table 2. Most frequent WTG models currently installed in Spain.

Manufacturer	Model	Unit rate power (kW)	Rotor size (m)	Average commissioning date	WFs equipped with the WTG
Gamesa	G87/2000	2 000	87	2008	8.63%
Gamesa	G52/850	850	52	2003	8.43%
Gamesa	G58/850	850	58	2003	8.06%
Gamesa	G90/2000	2 000	90	2008	8.06%
Gamesa	G47/660	660	47	2000	7.59%
Vestas	V90/2000	2 000	90	2008	5.34%
Acciona	AW-1500/77	1 500	77	2006	4.88%
Vestas	V90/1800	1 800	90	2007	4.12%
Gamesa	G80/2000	2 000	80	2006	4.03%
Made	AE-46/I	660	46	2001	2.62%

Fig. 2 includes two subfigures that show the location of the operative WFs in Spain (a). It can be observed that most WFs are located in the Northwest part of the Peninsula, Center North and Center South, where most wind resource is available. On the other hand, subfigure Fig. 2(b) shows the power density (aggregation of the WFs rated power). Fig. 3 shows the distribution of unit rated power of the WTGs installed in the WFs. It can be observed that many WFs in the Northwest coast (Galicia) and Center North (South part of Aragón) are equipped with low unit rated power WTGs despite the high available wind resource. The bigger unit rated power WTGs (Q1) are located also in the Center North (North part of Aragón) and Northeast coast (Catalonia) because there are the latest projects placed. The greater wind energy generation region in Spain (Castilla y León) seems to be equipped with medium size WTGs from the Q2 (unit rated power between 850 kW and 1.5 MW).



(a) (b)

Fig. 2. (a) Geographical distribution of installed WFs in Spain. (b) Wind power installed capacity located in Spain.

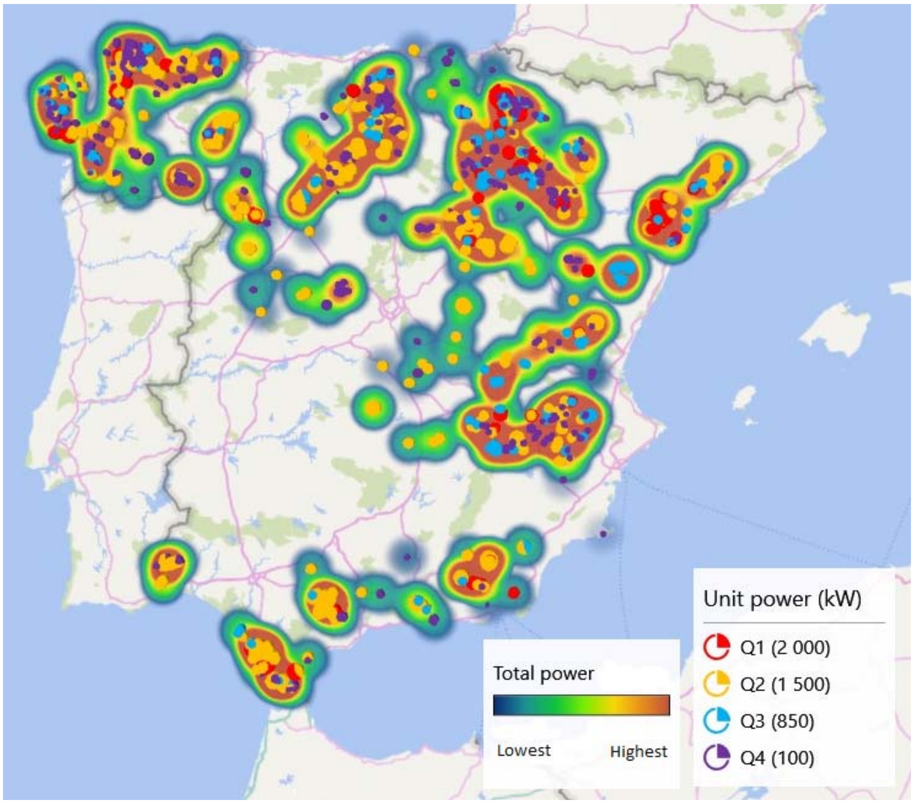


Fig. 3. Geographical distribution of unit power of the WTGs per quartiles in the Spanish Iberian Peninsula WFs.

2. Costs analysis and profitability model

2.1. Investment costs of a WF

The costs associated with investment in the installation of a WF, or capital expenditures, expressed as the specific investment required per unit of rated power (CAPEX), is the most important financial parameter in the determination of its economic profitability. Moreover, it is considered the most sensible parameter due to the trading capacity of the investor in an increasingly global market, which currently incorporates WTG manufacturers from emerging markets, who are reducing prices significantly [22].

According to [23], the highest cost in the breakdown of the installation of a new WF is associated with the costs of the WTGs, reaching 76% of the total cost in some cases. This cost is immediately followed by the grid connection costs, which can be estimated in 9% of the total and 50% of the auxiliaries.

In [22], the authors checked that the total installation costs of on-shore projects where about 70% less in 2016 than the actualized costs in 1983. Thus, it can be concluded that the average worldwide learning curve of this generation technology makes that doubling the installed capacity only increases 9% of the CAPEX. In [24], it is estimated that weighted average total costs have decreased 19% for on-shore projects in Europe between 2010 and 2016.

The lowest CAPEX for on-shore wind projects have been found in China and India, with weighted average total costs estimated to be USD 1 245 per kW and USD 1 121 per kW, respectively, in 2016. This represents between 11% and 16% reduction from 2010 costs. Furthermore, weighted average total costs have also decreased in Brazil from USD 2 390 per kW in 2010 to 1 994 per kW in 2016 [22]. North America has also competitive costs for on-shore WFs, with weighted average costs of USD 1 775 per kW in 2016 (22% reduction on costs from 2010) [24].

On the other hand, Asia (excluding China and India), Oceania, Central America and the Caribbean and South America (excluding Brazil) are the most expensive regions, with weighted averages total costs between USD 1 884 per kW and USD 2 256 per kW in 2016.

Moreover, according to the performed studies in [22]–[30], it can be observed that CAPEX trend is similar in most countries all around the world. First, a significantly decreasing trend is observed in the period from 1996 to 2004. Then, a rare demand growth of this technology in developed countries promoted by the introduction of new RES policies made capital expenditures of WF rise unexpectedly up to € 3 000 per kW in some cases. This overrated period seems to last until 2008. Finally, since 2008 and probably because of the financial worldwide crisis which stopped most RES inversions, CAPEX values show a decreasing trend again (of approximately 5% per year) until 2015. Although 2016-2018 values seem to show a rising trend again (see Fig. 4), these data must be taken with caution as they may be not statistically significant. Thus, it could be expected that, after 10 years, this technology can achieve its maximum maturity represented by stabilized costs between € 700 and € 850 per kW.

In summary, according to the worldwide prices analysis, it can be concluded that current CAPEX for on-shore WFs can be estimated between € 800 per kW and € 1 100 per kW as a worldwide average.

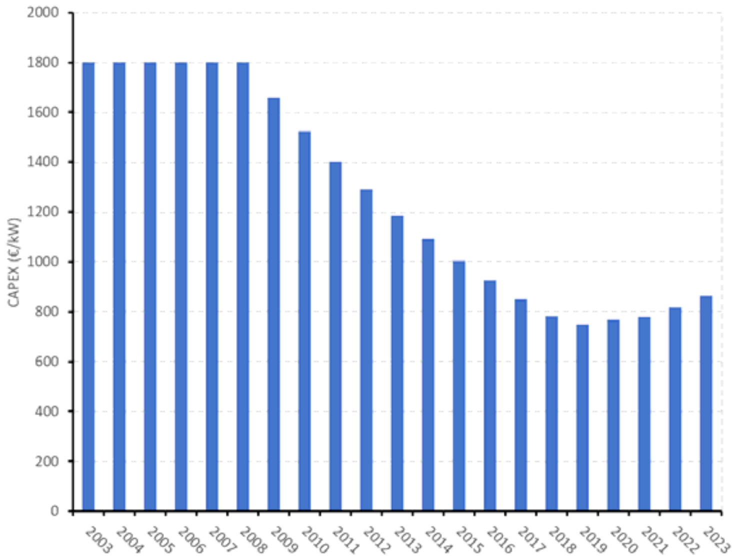


Fig. 4. Average CAPEX estimations for on-shore WF projects in the EU members for the period 1994-2023. Data from: [22], [23], [25]–[30].

2.2. Operation and maintenance costs of a wind farm

Operation and maintenance (O&M) costs, also called operational expenditures (OPEX), include all activities that are necessary to apply in an operative WF to ensure a safe, reliable, and continuous operation [6]. These costs can usually be breakdown in two categories:

- Scheduled operations: known and scheduled costs from the maintenance programme, land rental costs, taxes, utilities and insurance payments. They are usually fixed costs independent on the generated energy.
- Accidental operations: unplanned maintenance actuations in the WF to avoid a complete or partial unavailability of the generation plant. These costs use to change throughout the project lifespan and can be a function of the generated electricity or the operation time [31].

The O&M costs analysis carried out in [32] shows that the largest contributor to the average OPEX is the cost of spare parts, followed by labor costs. Actually, for the first 5 years after commissioning of the WF, the spare parts costs are estimated to be 30% of the total and, at the end of the project's lifespan, they can easily exceed 65%. This means that it must be considered an average costs increment of 11% per year on average. On the other hand, authors in [33] found that these costs increase 10% on average in the second decade of life of the WFs (with respect to the first one), which implies 1% per year increments in the second half part of the WFs useful lifespan.

Nevertheless, in the recent years some techniques have been developed to reduce O&M on large WF projects, highlighting: outsourcing, condition monitoring, mature aftermarket components, innovative rigging and tooling and record keeping. Thus, according to [25], in the period from 1980 to 2010, O&M costs have been reduced 61% in terms of installed power capacity, and 74% in terms of generated energy from the commissioning date (see table 3).

Table 3. Evolution of OPEX according to the commissioning date. Data source: [25].

Commissioning date	Power unit cost ($€·kW^{-1}·yr^{-1}$)	Generated energy cost ($€·MWh^{-1}$)
1980	69	35
1990	57	24
2000	28	10
2010	27	9

Authors in [34] explain this O&M costs reduction mainly because recently commissioned projects account with larger and more sophisticated WTGs, which benefit from scale costs and, thus, may experience lower overall OPEX in terms of € per kW and per year. Moreover, latest WTG models guarantee shorter downtimes and, as they have higher capacity, OPEX in € per kWh also suffer significant reductions. Nevertheless, O&M services market is getting more competitive, especially in Europe, USA and China [35].

Finally, some authors express O&M costs in terms of monetary units per installed power unit per year or per generated energy. Other authors represent OPEX in terms of monetary units per installed WTG [32]. In this case, according to the presented data, an OPEX model has been adjusted, as it can be seen in equation (1), including a term of costs per WTG units in the WF (*a*), a term of costs per nominal rated power (*b*) and a term of costs per generated energy (*c*). Moreover, decrement update of first year commissioning O&M cost has been included (*d*) and fixed to 2%, and O&M costs increment because of WF aging has been also considered (*e*) and fixed to 5%.

$$OPEX = aWTG + bP + cE. \tag{1}$$

In equation (1), $OPEX$ is the yearly operation and maintenance costs ($€·yr^{-1}$), WTG is the number of WTGs in the WF, P is the installed rated power (kW), E is the yearly energy output ($kWh·yr^{-1}$).

2.3. Profitability analysis

Currently, the retributive system based on feed-in-tariff (FIT) incentives is suspended in many countries, such as Spain, both for new and repowering projects. Thus, profitability of the new power plants will be defined just by their operation against the electricity market.

The Net Present Value (NPV) of the investment is calculated from the yearly cash flows (CF) calculated as the difference between the incomes from the energy sold and the O&M costs, discounting back to its present value at the discount rate (*r*), as expressed in the equation (2), where *n* is the age of the WF.

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - CAPEX \times P. \tag{2}$$

NPV is the account for changing monetary unit valuations. In other words, the NPV is a measure of today's value of revenues or costs to be incurred in the future [36].

Other related economical variable, related to the NPV, that accounts for the profitability of the inversion is the Internal Rate of Return (IRR), which is defined as the interest rate at which the NPV becomes zero in the expected lifetime of the inversion, as it is defined in equation (3),

$$CAPEX \times P = \sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i}. \tag{3}$$

A positive NPV value means that the inversion obtains a positive benefit in the analyzed period, while a negative value means economic losses. Accordingly, an IRR value greater than the discount rate *r*, makes the inversion attractive for investors, while lower values help them to discard the inversion option.

The opportunity cost is commonly defined as the inversion costs of the available resources against the best available inversion alternative. It is usually determined by the expected profitability of the inversion in terms of future benefits, which in the end, are related with the NPV and/or the IRR. This widely known economic model for inversion profitability evaluation must be adapted in this case taking into account two relevant factors: (i) the true valorization of the old WF, and (ii) the OPEX evolution in time. While the OPEX evolution formula has been already described with expression (1), the true valorization of the old operating WF is not a trivial task. There is not an official methodology to determine the monetary value of an operative WF. Many authors use to consider this term negligible [6], [10], but it can have a significant impact in the profitability analysis. Experts advocate three different methodologies to estimate the residual value (RV) of a WF:

- Linear amortization in time of the initial CAPEX.
- The sum of the expected CF in the next 5 following years.
- The NPV of future cash flows until the end of the WF useful life.

In the proposed model, if none of the options results in a negative value and variance between the three values is small enough, the mean value among these three options have been considered. Otherwise, negative values and outliers are discarded from the average calculation.

It must be highlighted that, as the RV of the old WF has been considered as an extra in the CAPEX of the repowered WF, the opportunity cost (OC) between repowering and going on the operation of the old WF is just the NPV value of the repowered WF. In a similar manner, the same consideration can be applied to the IRR calculation. Thus, the decision tool for repowering can be expressed as:

$$OC = \sum_{i=2}^{n} \frac{\sum_{h=1}^{8760} p(h)E(h) - OPEX(co, age)}{(1+r)^i} - (CAPEX \times P + RV), \tag{4}$$

where *p(h)* is the electricity sale price at hour *h* (€·kWh^{-1}) and *E(h)* the sold electricity energy at the same hour *h* (kWh). This expression can be approximated by the following one:

$$OC = \sum_{i=2}^{n} \frac{\bar{p}(i)E[1-u(i)](1-dg^i)}{(1+r)^i} - (CAPEX \times P + RV), \tag{5}$$

where $\bar{p}(i)$ is the weighted yearly average electricity sale price (€·kWh^{-1}) for the year *i*, *E* the average annual sold electricity energy by the WF (kWh), *u(i)* the unavailability rate of the WF function with age and *deg* the degradation rate due to the WF aging. The unavailability or downtime rate function can consider either a constant probability downtime rate, a wear out failure pattern or a bathtub failure curve. Probably, the most realistic failure pattern in this case would be the wear out, as initial birth failures occur after the WF economic operation. Thus, the unavailability rate function should be in the form seen in equation (6).

$$u(i) = \alpha e^{i-\beta} + \gamma, \tag{6}$$

where α, β and γ are model constants.

2.4. Generated energy estimation

The generated energy of a WF is related with the available wind resource of the WF location at the hub height and the WTG rated power curve. Thus, data from the Spanish Wind Atlas developed by IDAE has been used to estimate the wind profile for each WF location [37]. The Spanish Wind Atlas implements a meteorological model and simulates the wind resource for the complete Spanish Iberian Peninsula from discrete reference data points (calculation grid). The simulation and prospecting of the long-term wind resource has been used, studying its interaction with the topographic characterization of Spain, without carrying out a specific measurement campaign. Modern mesoscale and microscale modeling techniques offer a very effective solution to these problems: they effectively combine the use of a sophisticated atmospheric simulation model, capable of reproducing wind patterns on a large scale, with a micro-scale wind model that responds to terrain features and topography. In this way, wind potential studies can be carried out in large regions with an acceptable level of approach. Results have been validated by the comparison of several yearly wind energy production data from the Spanish TSO, Red Eléctrica Española (REE).

The wind distribution has been evaluated at the hub height of each WF, obtaining the effective wind speed, the annual specific wind power, the equivalent hours, and the capacity factor as results. The evolution of the average effective speed (wind speed value that would gather the same annual wind energy if the wind distribution were constant) with the commissioning year is shown in Fig. 5. It can be concluded from the analysis of this figure that the best locations for WF projects installation (higher effective speed) were occupied first. Moreover, the trend is grade 2 polynomic. This means that, without considering the repowering option, new WFs are forced to be placed in worse wind resource locations according to the wind resource and best locations are covered in an accelerated manner.

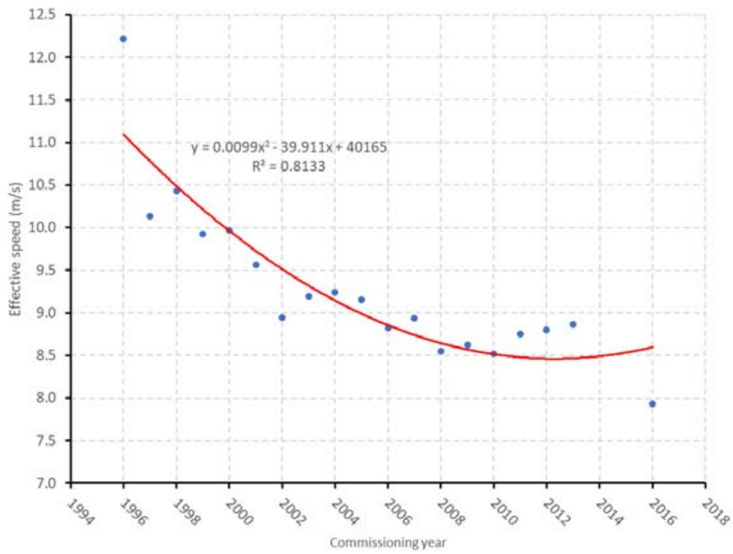


Fig. 5. Wind effective speed depending on the commissioning year.

2.5. Application to the case study

The application to the case study implies a large number of assumptions and particular considerations that can be significantly different from one project to another, and that must be taken into account for the results replicability. Interpretations in the cost categorization approaches can lead to unexplained results deviations. The main assumptions made are the choice of discount rate, aged WF price, lifetime and degradation of energy generation over the lifetime. O&M costs, both fixed and variable, are a significant part of the analysis of wind energy [22], [30].

- A useful life of 25 years for WFs is established. Thus, the remaining useful life of an aged WF has been calculated as the difference between 25 years and the age of the WF.
- The economic operation year of the WF is 2020, because it has been taken into account one year for the WF construction (realistic scenario).
- Year of analysis: 2018.
- The discount rate of future cash flows of a repowered WF has been established in 10% in accordance a conservative scenario in the provisions of [38].
- The sale price of electric energy in the wholesale market has been estimated in € 46 per MWh, as seen in the last years market trend, according to [39].
- The estimated evolution of the sale price of the electric energy is established at 1%.
- The degradation rate has been established at 0.8% as an average value from those considered in the literature, which shows very disparate data, between 1.6% for the United Kingdom [40] and 0.5% for Sweden [41].
- Energy calculations have been conducted considering an air density of 1.225 $kg{\cdot}m^{-3}$ at the sea level and with an ambient dry bulb temperature of 15ºC.
- The local ambient temperature for energy production has been set to 15°C.
- For simplicity in calculations and results interpretation, the unavailability rate function has been neglected.
- It has been considered 5% per year OPEX increments of a WF since the commissioning year.
- The reference annualized component of the O&M costs attributable to the number of WTG that constitute the WF is set at € 10 000 per WTG for reference year 1994.
- The annualized component of the O&M costs attributable to nominal power is set at € 10 per kW and year for reference year 1994.
- The annualized component of the O&M cost attributable to the generated energy is set at € 0.01 per kWh for reference year 1994.
- Because of the first analysis year is considered to be part of the WF construction, incomes for this year are considered as zero.

3. Results and Discussion

The 1 067 WFs that currently are part of the Spanish wind energy generation system have been simulated and analysed according to the economic profitability model described in the previous section.

Fig. 6 shows the called *"specific OC"*, defined as the ratio of the calculated opportunity cost per unit of rated power of each WF in the study, as a function of the commissioning year of the WF. Blue dots in this figure represent the weighted average value for each year, while the error bars show the minimum and maximum values, respectively. Although the values distribution is observed to have some variability, the weighted average values show a clear descendent trend, characterized by a linear regression with high correlation (R^2>0.85). This observation demonstrates that the newer is the repowered WF, the less profitable is the repowering option. Moreover, WFs commissioned after 2008 show negative values for the specific OC, which means that the repowering of these WF will never reach benefits along the WF expected useful lifespan (which in the performed simulation was established in 25 years, 5 years more than IEC estimations).

It can be concluded that the older is the WF to repower, the greater is the opportunity cost, as the location offer higher wind resource (first locations account with higher wind effective speed as observed in Fig. 5) and their residual value is significantly lower. In addition, if we focus the analysis in the last commissioning years, the observed OC for aged WF in contrast of repowered WF shows a significant reduction becoming almost negligible, because the technical differences on WTGs are very small. Thus, according to these results, although most WFs can be interested in the repowering alternative, it results much more attractive for the oldest ones, especially those commissioned before 2000.

Finally, another important remark deduced from Fig. 6 is that, although most WF commissioned before 2008 show positive values for the specific OC, some of them show negative values. This effect must be observed with care as it is generally related with very expensive CAPEX of the WF which increased the WF's residual value

(RV). Other reason for negative specific OC for these WF can be lower energy generation than expected or extremely high O&M costs. Nevertheless, it must be taken into account that the discount rate has been set at 10%, which is a certainly conservative scenario (currently in Spain, the estimated reasonable return established by the Government for RES inversions is set at 7.4%, and it is expected to be revised downward).

Furthermore, in Fig. 6 it can be observed that there were no commissioned WF in the period 2014-2015 and the projection of the specific OC for future WF installed in 2020 estimate almost € -500k per MW.

On the other hand, Fig. 7 correlates the specific OC with the wind effective speed for all WFs included in the study. Results show a clear rising trend with linear correlation (R^2>0.81) between these two parameters, which reflects the impact of the location (wind resource quality) with the inversion profitability. An increment of 1 $m \cdot s^{-1}$ in wind effective speed, can conduct to almost € 200k per MW. As stated in the introduction, full repowering of a WF implies the installation of new WTGs, which are characterized by higher tower heights, where wind speed increases due to the vertical wind speed profile.

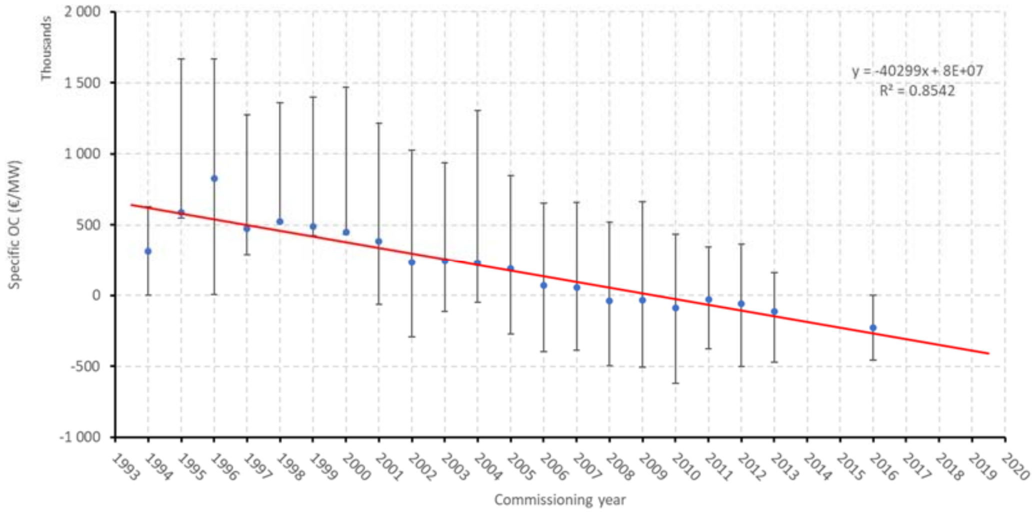


Fig. 6. Specific OC (OC per unit of rated power) as a commissioning year function.

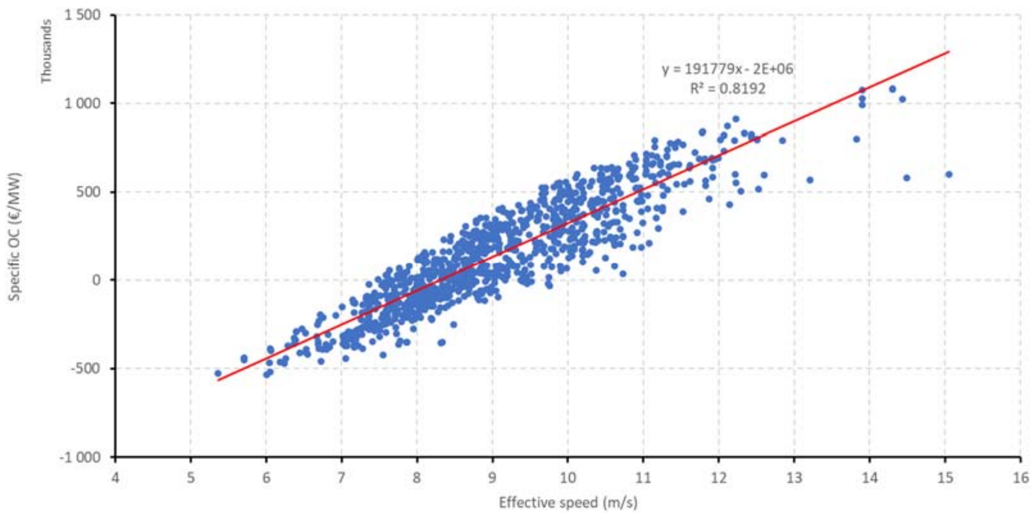


Fig. 7. Specific OC (OC per unit of rated power) as a function of the wind effective speed.

Fig. 8 shows the same analysis than Fig. 7 in the case the RV of the repowered WF were neglected. Comparing Figs. 7 and 8 it can be observed that the RV does not affect the positive trend with the wind effective speed, but explains the data dispersion as Fig. 8 shows a higher correlation (R^2=0.9471). However, this simplification describes a less realistic scenario.

As stated before, the OC has been calculated for a discount rate of future cash flows estimated on 10%, which can be considered quite conservative. Thus, the IRR has also been analyzed to evaluate the potential for generating wealth at lower rates (see Figs. 9 and 10).

Fig. 9 shows the IRR for repowering the WF as a function of the commissioning year. As expected, observed trend is similar to the one obtained for the specific OC in Fig. 6: a negative linear correlation. However, it can be also observed that the IRR results always positive even for the latest WFs, considering all the assumptions. Repowering WFs commissioned before 2000 can reach IRR greater than 15%, while repowering WF commissioned between 2000 and 2007 are in the range for IRR between 10% and 15%. The highest profitability seems to be achieved for WFs installed in 1996, while the lowest are the newer ones commissioned in 2016 with almost 5%. Some specific WFs can reach IRR greater than 40%, while for the same commissioning year, other WFs can have almost negative IRR values. The location of the WF, the CAPEX and the OPEX are the main reasons of these discrepancies.

Similarly, to Fig. 7, Fig. 10 shows the IRR correlation with the wind effective speed, which also shows a positive linear trend (R^2>0.78).

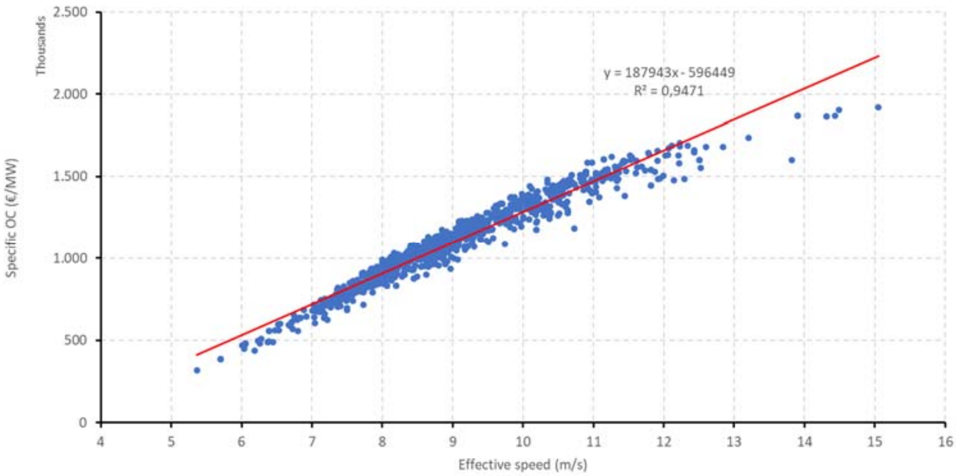


Fig. 8. Specific OC (OC per unit of rated power) as a function of the wind effective speed considering the WF's residual value (RV) negligible.

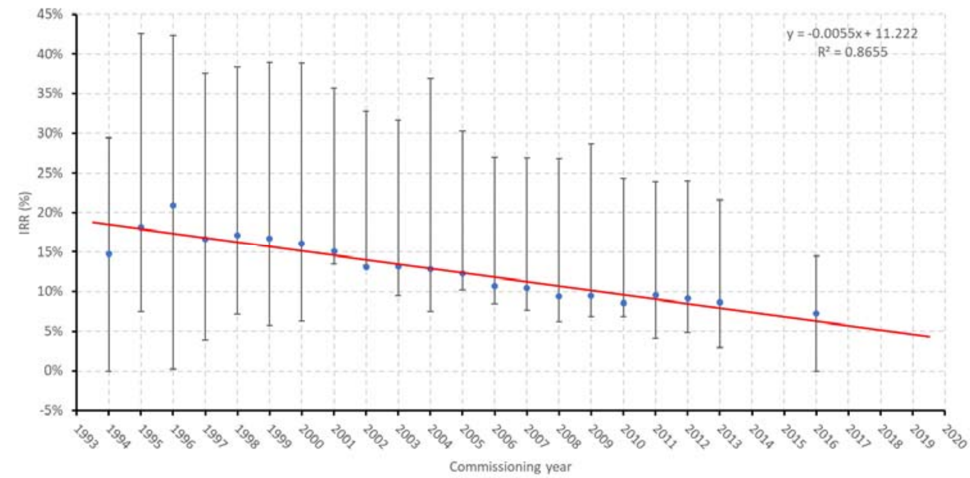


Fig. 9. IRR as a function of the commissioning year.

The IRR correlation with the wind effective speed shown in Fig. 10 points out a 2.5% increment of the IRR per 1 $m \cdot s^{-1}$ of wind effective speed. Only very high wind effective speed (greater than 14 $m \cdot s^{-1}$) show less increment and be slightly down the trend.

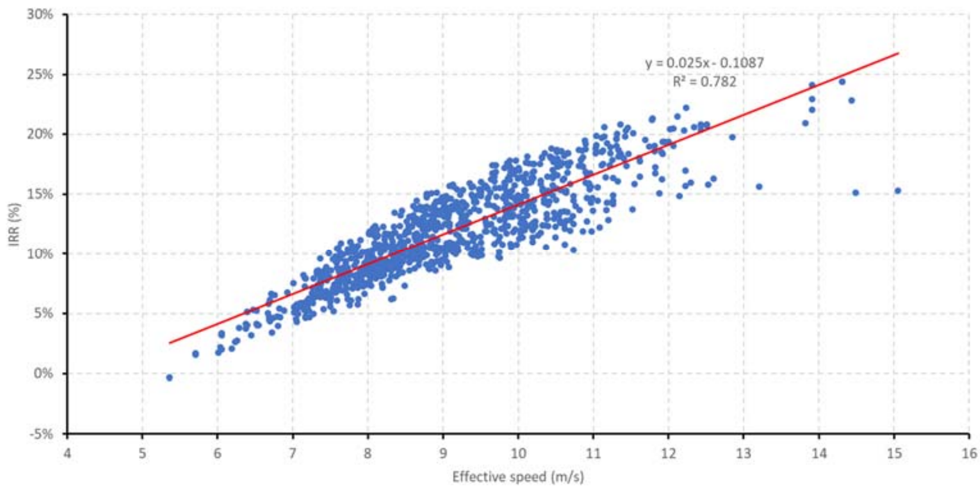


Fig. 10. IRR as a function of the wind effective speed.

Finally, Tables 4 and 5 and Figs. 11 and 12 show the location and characteristics of the best and worst WFs for considering the repowering alternative as an inversion option, according to the performed simulation. It can be observed in Table 4 that the *"gold options"* are characterized by a relatively high wind effective speed (in the range between 11 and 14 $m \cdot s^{-1}$), a significant reduction on the number of installed WTGs per WF between the 60% and the 81% (which means a reduction in the environmental impact) and a total rated power capacity increment between 300% and 5 000%. Actually, the 20 best WFs would imply an aggregated increment in installed wind capacity from 246 MW to 1,024 MW (416%).

Table 4. Characteristics of the top 10 WFs with higher opportunity costs.

WF description	Number of aged WTGs	Unit rated power of aged WTGs (kW)	Total rated power (MW)	Commissioned year	Num. of repo. WTGs	Unit rated power of repowered WTGs (MW)	Total rated power of repo. WF (MW)	Wind effective speed (m/s)	Opportunity cost (k€)	Specific OC (€/MW)	IRR (%)
Levantera A	1	150	0.15	1995	1	8	8	14.31	8 652.27	1 081.53	24.39
Levantera B	5	100	0.50	1995	2	8	16	14.31	17 294.94	1 080.93	24.38
Monteahumada I A	1	330	0.33	2004	1	8	8	13.91	8 588.50	1 073.56	24.10
Monteahumada I B	1	800	0.80	2004	1	8	8	13.91	8 229.28	1 028.66	22.95
La Locustura	1	1 650	1.65	2000	1	8	8	14.44	8 183.90	1 022.99	22.81
Monteahumada I C	1	1 320	1.32	2004	1	8	8	13.91	7 919.63	989.95	22.03
Hinojal/Tahivilla	1	600	0.60	1999	1	8	8	12.23	7 281.56	910.19	22.21
El Cabrito	90	410	36.90	1999	19	8	152	12.12	132 612.24	872.45	21.49
La Joya	12	500	6.00	1996	3	8	24	11.79	20 134.69	838.93	21.32
Bustelo	76	330	25.08	1998	15	8	120	11.78	100 375.84	836.46	21.20

On the other hand, in Table 5 the 10 worst WFs according to the opportunity costs are included. In contrast with those collected in Table 4, these WFs are characterized by a relatively high wind effective speed (in the range between 5 and 7 $m \cdot s^{-1}$), a low reduction on the number of installed WTGs per WF, between the 43% and the 71%, and a total rated power capacity increment just between 100% and 303%.

Finally, Figs. 11 and 12 show the geographical location of the WFs grouped by quartiles of the specific OC and IRR, respectively. The quartile limits are specified in brackets.

Table 5. Characteristics of the bottom 10 WFs with higher opportunity costs.

WF description	Number of aged WTGs	Unit rated power of aged WTGs (kW)	Total rated power (MW)	Commissioned year	Number of repowered WTGs	Unit rated power of repowered WTGs (MW)	Total rated power of repowered WF (MW)	Wind effective speed (m/s)	Opportunity cost (k€)	Specific OC (€/MW)	IRR (%)
Tallisca	20	2000	40	2010	11	8	88	6.01	-47 000.44	-534.92	1.76
Pucheruelo	27	850	23	2002	10	8	80	5.36	-41 952.13	-524.40	-0.31
Las Cabezas (Fase B)	7	2000	14	2010	4	8	32	6.05	-16 545.77	-517.05	2.04
Loma Viso II	1	3000	3	2009	1	8	8	6.24	-3 770.96	-471.37	2.66
Refoyas	33	1500	49.5	2006	16	8	128	6.04	-59 571.11	-465.40	2.21
Las Lomas	10	1500	15	2005	5	8	40	6.18	-18 574.28	-464.36	2.09
Lecrín	6	2000	12	2008	3	8	24	6.73	-10 970.13	-457.09	3.43
Peña Alta	34	660	22.4	2001	10	8	80	5.71	-35 947.43	-449.34	1.57
Cerros Pelaos	2	1500	3	2007	1	8	8	6.26	-3 551.69	-443.96	2.75
Peña Alta	7	850	6	2001	3	8	24	5.71	-10 634.09	-443.09	1.64

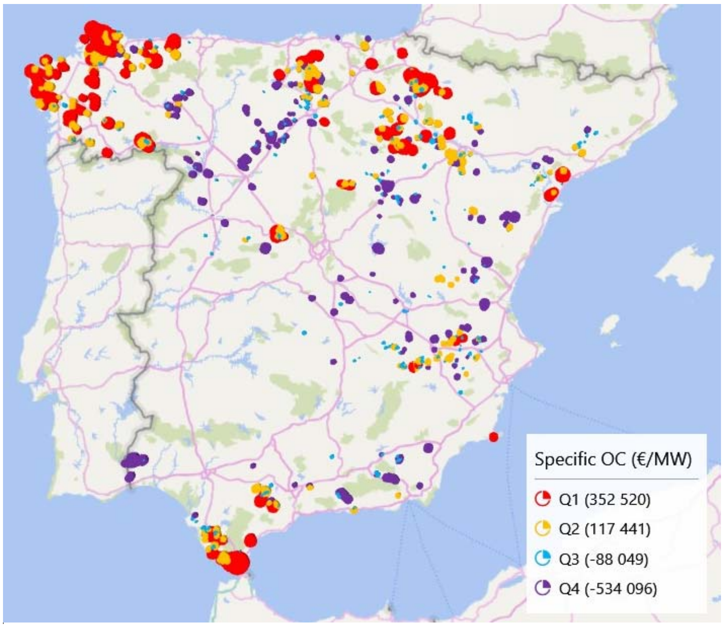


Fig. 11. Geographical distribution of the specific OC values for repowered WFs.

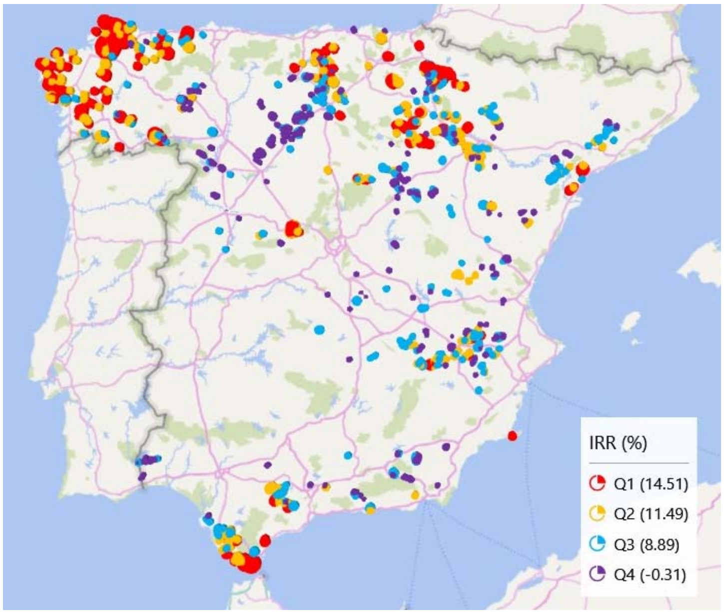


Fig. 12. Geographical distribution of the IRR values for repowered WFs.

Fig. 11 shows that most Q1 WFs are located in the Spanish region of Galicia (Northwest), some parts of Aragón (Northcentral) and in Cádiz (Southcentral), while Q4 WFs belong mainly to Castilla y León (Northcentral) and Levante (East coast). Nevertheless, geographical distinctions should not be made, as different characteristics (CAPEX, OPEX and RV) WFs are mixed in the Spanish geography. Thus, the economic profitability of the repowering alternative is not just a question of geographical location or wind resource. Similar observations can be conducted in Fig. 12, where the IRR is represented, as expected.

To summarize results, Table 6 shows the number of WFs and the involved rated power increment for different IRR segments.

Table 6. IRR data summary.

IRR (%)	Number of WFs	Repowered rated power (MW)	Rated power increment (%)
>15%	226	28 055.84	184.43
10-15%	465	9 933.15	176.49
5-10%	341	8 741.18	144.45
<5%	36	712.66	157.07

4. Conclusions

The Spanish wind system is characterized by an advanced age on average, as 78% of the WTGs stock have a minimum age of 10 years. In addition, in 10 years, it is expected that 7 GW of installed wind rated power will exceed 25 years of useful life, which will mean that the Spanish WTG stock will be obsolete. This situation makes mandatory for energy planners and RES investors to evaluate the repowering alternative. This decision will have a great impact in the Spanish wind energy market, as it is estimated up to 65 GW of rated power potential for repowering. Moreover, the full repowering of such power capacity will impact positively in the Spanish generation capacity, guaranteeing higher quality, higher efficiency rates, lower breakdowns and a boost on the WTG's learning curve. Undoubtedly, the repowering alternative is completely aligned with both national and European energy targets for a future decarbonisation power generation scenario.

The disadvantages of the repowering, mainly administrative, do not suppose an insurmountable barrier to dismiss its development and promotion, at the time its expected benefits will largely compensate the disadvantages.

The unclear valorisation of the residual value of an operating WF difficult owners to take the repowering alternative. By the proposed economic model which not only incorporates the decommissioned WF residual value as an added cost to the new CAPEX, but also energy generation capacity degradation and time evolution of the O&M costs, it has been observed that the repowering alternative can be highly profitable and an acceptable alternative for more than 38 GW repowered rated power.

Although the cost of investing in a repowered WF may be diminished by the use of part of the existing facilities, an assessment of the aged WF is necessary, as the owner will demand as compensation. In addition, a grace period estimated in one year, is necessary to be considered for the dismantling of the old WF and the commissioning of the new one. Nevertheless, the investment in repowering an operative WF can be very attractive in absolute and relative terms, especially, if old WTG and high wind resource join in a WF. This can be interpreted as an opportunity to improve the wind resource exploitation.

The opportunity cost is very sensitive to multiple parameters, which opens a wide spectrum of analyzable scenarios. The main parameters are: price of electricity, discount rate, the estimation of the residual value of the operative WF, lifetime expectancy and degradation rates, O&M costs (both fixed and variable) and, of course, the initial investment. For the latter, important oscillations are foreseen due to the commercial tensions existing globally, so it may be the most important factor to study in the future.

Repowering requires a completely new and stable normative framework, which must help to achieve the EU energy and climate policy targets for the near and long-term future, by the prioritization and promotion of the installation of the most efficient and sustainable generation systems possible. The repowering alternative is a profitable investment itself that generates a lot of added value, and that will help to relaunch the development of wind energy in Spain. However, the lack of specific regulations is holding back the development of a larger market which could offer a sustainable growth in the medium term.

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