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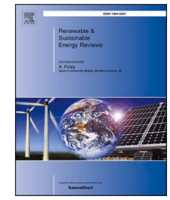

Multi-dimensional barrier identification for wind farm repowering in Spain through an expert judgment approach

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ABSTRACT

Spain was one of the pioneers in the deployment of wind energy systems worldwide and thus since 2014 has a potential for repowering that reaches between 3.3 and 8.7 GW in 2021 (12%–32% of its current installed wind capacity). However, despite the technical and economic advantages, we have observed little interest from promoters in the repowering of already amortized wind farms. The aim of the proposed study is to depict the background framework of barriers for repowering wind farms, which is specially affecting to Spain, but that can also extend to other EU countries. Therefore, we conducted a systematic survey study with academics, promoters, financial experts, manufacturers, operators, maintainers and policymakers to identify and understand the existing real and practical barriers. As a result, we have identified 34 major barriers covering five categories: technical issues, economics, environmental considerations, social concerns, and regulatory and administrative hurdles. We then asked the experts to rate these barriers based on their impact or relevance. We found that the experts agree that regulatory and administrative barriers have the maximum impact, while economic, environmental and technical barriers have only a mid-high impact. Therefore, we can conclude that, in general, the Administration must develop a concise and stable regulatory framework for all RES, especially for repowering projects, and carry out a review of both the technical requirements and the incentives schemes, with a focus on energy efficiency.

1. Introduction

In Spain, since 2010, and the elimination of subsidies for renewable energy sources (RES) power plants [1,2], the amortization of recently built combined cycle units and the long-term uncertainty in the regulatory framework caused a significant slowdown in the installation of new RES power. However, the goal of the European Union to produce 100% RES electricity by 2050 [3] is causing Spain to redefine its energy mix. Currently, it intends to produce 74% of its electricity needs with RES by 2030 [4], and thus, the Spanish Government is organizing specific RES auctions [5]. The latest auctions showed a high level of interest with promoters to develop new wind and solar projects, even without subsidies [6]. This is mainly caused by the drastic drop in costs and the increase in the maturity of wind and solar photovoltaic technologies over the past decade [7]. Particularly with wind energy, where costs have decreased from approximately € 2000 per MW in 2009 to € 750 per MW in 2018 (a 62.5% drop) [8].

Whilst the solar resource is more uniformly distributed through the region; the wind resource is more influenced by local aspects. Although there are still locations with great potential for the location of wind farms (WFs) in the Spanish territory, the best locations are already occupied by wind farms of on average over 15 years old [9], which represents 75% of their expected life span [10]. What draws our attention in this paper is the lack of interest from promoters in repowering those wind farms close to the end of their lifespan, despite the current advantageous scenario. Therefore, we have conducted a systematic study with representatives of the wind energy field (academics, promoters, financial experts, manufacturers, operators, maintainers, and policymakers) to identify and understand the main technical, economic, regulatory, environmental, and social barriers which are obstructing the repowering of the oldest wind farms in Spain. We then attempted to depict the main measures to overcome them.

The "full repowering", or simply "repowering", of a wind farm

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Nomenclature

Acronym	*Description*
CapEx	Capital Expenditures
FiT	Feed-in Tariff
OpEx	Operation Expenditures
PoC	Point of Coupling
RES	Renewable Energy Sources
TSO	Transmission System Operator
USA	United States of America
WF	Wind Farm
WTG	Wind Turbine Generator

consists of replacing its wind turbine generators (WTGs) with new ones. This action can be carried out since the installation costs have been amortized until the end of the useful life of the wind turbine generators. Although repowering a wind turbine generator before the end of its useful life means the loss of part of the profits that it still can generate and the new investment cost, but, we must also take into consideration that we can significantly increase the energy generation capacity, and therefore the revenues, with a new wind turbine generator [11]. Due to the rapid improvement of this technology in the last few decades, (wind turbine generators have doubled their average rated power in the last 15 years in the USA [8], 10 years in other markets such as Canada, Brazil, or Sweden [7] and approximately 8 years in Spain according to installation data) new wind turbines offer a higher rated power output and better specifications for the same CapEx (Capital Expenditures) long before the end of their expected life span. Even when considering the need to upgrade part of the wind farm infrastructures, it is an attractive option for wind farms owners [12,13]. Furthermore, repowering a wind turbine generator near the end of its lifespan can reduce its maintenance and operation costs [11,14] and eliminate the uncertainty of wind turbine failure rates in comparison with actions to extend its lifespan [15]. Finally, we must note that repowering a wind farm could also allow a reduction in the number of wind turbine units, whilst keeping or even increasing its capacity factor, which has been widely demonstrated in the literature [11,14,16,17]. By reducing the number of wind turbines, we can reduce the environmental impact, including landscape damage [14,17] and inconveniences to the local wildlife [17], although some ecologists claim that the higher the height and size of the wind turbine generators, the greater the impact, even with fewer units in the field. Moreover, we observe a certain dichotomy in the vision of citizens and political leaders concerning wind energy, as occurs with other sources of energy, such as hydroelectric power plants, apparently environmentally friendly, but undesirable in the backyard [18].

The Spanish wind power system is characterized as being of advanced age, as 86% of the wind turbine generators stock are at least 10 years old [9]. As can be seen in Fig. 1, since 2014 there is a potential for significant repowering in Spain. This potential has increased the range from [5, 1075] MW in 2014 to [3.3, 12.0] GW in 2021. If we talk about the number of wind turbine generators (older than 15 years) with the potential to be repowered, we find up to 2087 units in 2014 and 13, 589 units in 2021. However, the actual repowered values are far away from this theoretical potential, with only about 138 MW currently repowered. Since the end of the 1990s, the Spanish state developed a regulatory framework that promoted the important development of renewable energy sources (RES) [19–21], through a remuneration scheme higher than the market price of electricity. Later, in 2007, the installations found in the advantageous Feed-in Tariff (FiT) supporting legislation [22] (currently not in force). Since 2010, the elimination of subsidies for new RES power plants [1,2] significantly slowed down the development of new RES facilities, including wind energy projects. Since 2020, the Spanish Government has been organizing specific RES auctions [5], but they do not include a specific mechanism to promote repowering. Therefore, we have observed that only six projects of wind repowering have been executed in the period 2014–2021 [23–25].

In contrast to Spain, in Europe and the USA, repowering is considered a sustainable way for the deployment of wind energy [26,27]. Denmark plans to conduct significant repowering actions increasing its wind power capacity with fewer wind turbine generators [28]. Denmark was one of the first countries in the European Union to deploy wind power on a large scale and, thus a large number of the country's active wind turbines are expected to be decommissioned in the coming years [29]. On the other hand, in Germany repowering opens access to fixed Feed-in Tariffs for another 20 years, which increases its attractiveness for investors [30]. Finally, in the USA we observe a repowering capacity of 2899 MW in 2020 [31], with more than 50% of its installed wind capacity dating from the 1980s [32].

The proposed study aims to depict the background framework of

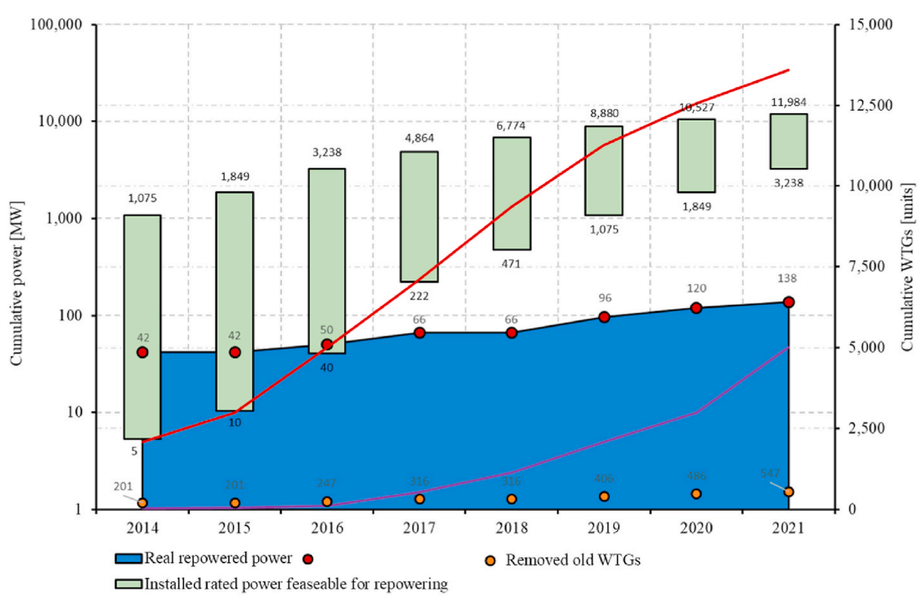

Fig. 1. Potential for repowering wind farms in Spain. Own elaboration. Data from Ref. [9].

barriers for repowering wind farms, which are specifically affecting Spain, but that can also be extended to other EU countries. Furthermore, our aim is not only to identify possible barriers but also to benchmark them according to their impact in order to identify the most prominent ones in which policy-maker must emphasize their efforts to overcome them. In this paper, in contrast with the classical techno-economic studies based exclusively on the analysis of economic revenues and profitability, we have applied a holistic approach. This approach results mandatory in energy planning or economy, not only because they are affected by multiple factors, but also, according to several works of Prof. W. Brian Arthur in the Economy field, because they are not necessarily in equilibrium: energy agents (generators, consumers, investors, policymakers), in a similar way to economic agents, constantly change their actions and strategies in response to the outcome they mutually create [33,34]. Thus, we have identified and scored real existing technical and economic barriers and regulatory, environmental, and social ones, which are usually not mentioned in the academic literature but remain underneath real-life investment decisions. Our analysis is supported by a panel of experts with distinct roles (and interests) in the wind energy industry. The analysis of the results of surveys done to agents with different roles in the wind industry has proven to be effective in other socio-economic research works, such as in Ref. [35] where the author studies the relation of the innovation strategies of the wind industry in Brazil with the sustainable development; or the evaluation of the effectiveness of the introduction of energy policies, such as in Ref. [36], focused in the new policies supporting the introduction of wind electricity in Denmark. The overall followed methodology (to the best of our knowledge) is quite novel in the field of RES and this approach can be extended to other fields of study regarding energy planning [37] and the obtained results can be easily extrapolated to other regions under similar circumstances regarding wind energy planning and deployment.

Our main contributions with this paper to the state of the art are:

- We have identified and grouped the main technical, economic, regulatory, environmental and social barriers for applying a repowering strategy by a systematic analysis of the conclusions and experiences of a panel of experts from the wind industry.
- We have scored the identified barriers according to their potential impact on the repowering decision, in order to help policymakers better understand current energy policy weaknesses and incentive needs.
- We have proposed a feasible main framework of general measures to overcome the identified barriers and promote wind repowering.

The remainder of the paper is structured as follows: in the next section, we describe the proposed method for surveying the experts to identify the barriers and the adopted criteria to score them. Then, we present the results section. We show the initial survey to the experts and a concise summary of their answers and comments. Next, we conduct a brief discussion of the obtained results according to the existing literature on the topic (including grey literature) and propose some measures to overcome the observed barriers. Finally, we depict the main conclusions that we have obtained from our study.

2. Materials and methods

To conduct the proposed study, we first undertook a broad review of the recent scientific publications and grey literature related to the topic. This helped us (i) to identify potential barriers for repowering extrapolated from other studies, and (ii) to identify the recognized authorities on this topic and, thus, better select the panel of experts. The experts were contacted in three rounds, similar to our previous study which had the purpose to identify the institutional and economic non-market barriers of photovoltaic self-consumption in Spain through an expert judgment approach [38].

In the first round, we asked 30 questions to the experts. This questionnaire was prepared both in Spanish and English and included a brief introduction with general instructions (to help complete the questionnaire), the description of the purpose and context of the survey and the basic definitions of "full repowering" [13,39,40], "partial repowering" [13,41] and "useful life extension" [39,42] in order to avoid confusion with the terms. The surveys were mailed directly to the experts, who were given several weeks to return their completed surveys. The experts could answer all the suggested questions or just those they wanted to, most completed the questionnaire answering all the questions. We also gave them the opportunity to add extra comments, however, almost all of them declined to add anything.

Once we received the completed surveys, we analyzed and classified their comments to identify the potential N barriers (in this case, we identified $N = 36$ potential barriers). The questionnaire was organized into 3 groups; (i) technical aspects (10 questions), (ii) economic issues (6 questions) and (iii) social, environmental and regulatory concerns (13 questions), we used this classification to identify a preliminary set of barriers for each group. We then prepared a survey with this set of barriers and sent it to all the experts (including those who did not participate in the first survey) so that each expert could rank them, add new ones (not properly identified in the first phase) or discard them. If the median of the scores obtained by a barrier was lower than the minimum (5.0) the barrier was discarded. On the other hand, if the median of the scores of each barrier was higher than the minimum, we analyzed if it could be grouped with others. In that case, the definition of the group of similar barriers was revised to include all the related aspects. Otherwise, the barrier was included in the final list as an independent one.

Finally, once the full list of barriers was analyzed and grouped, we sent it to the panel of experts (including again all the potential experts, even if they did not participate in the two previous queries) in order to validate the list and ask for possible measures to mitigate or eliminate them. The complete process is described graphically in the flowchart of Fig. 2.

As stated before, a broad review of recent scientific publications and grey literature about the topic helped us to identify the recognized experts in the field. For this review, we focused on wind energy repowering studies, wind energy planning and regulations and research on renewable energy policies. We also contacted the manufacturers with the major market share in Spain, the regional and national energy regulators in charge of wind energy regulations, regional and national promoters through the National Association for Wind Energy and local operators and maintenance companies. In total, we contacted more than 200 agents, but we only received a positive answer from 25 of them in the first phase, and 37 in the second and third phases. We consider that it is still a representative sample, considering that, manufacturers and promoters are reticent to provide information. The composition of the panel of experts for the first phase can be seen in Fig. 3 (a), while Fig. 3 (b) shows the experts who collaborated in phases 2 and 3. All the experts were contacted in the period from August 2020 to December 2020.

For the identification of real-life barriers to repowering wind farms, we prepared a questionnaire of 29 questions which was organized into three sections: (i) technical, (ii) economic and (iii) social, environmental, and regulatory concerns. This initial classification is based on the work of [43] and the theoretical framework presented in Ref. [44], who observed that energy barriers can be classified into behavioral aspects, market failures, environmental restraints, institutional barriers and economic non-market failure hurdles. In our case, we reduced and grouped the categories proposed in Refs. [43,44] in accordance with the experts' findings. Furthermore, we formulated the questions in such a way we did not ask for specific potential barriers directly, but we asked about general concerns related to the potential barriers. This allowed us to identify new barriers and avoid wrong initial assumptions. We formulated most of the questions following the structure proposed by Weber [44] ("What is an obstacle to whom reaching what?"). However, we tried to overcome some of the limitations of the classical barriers

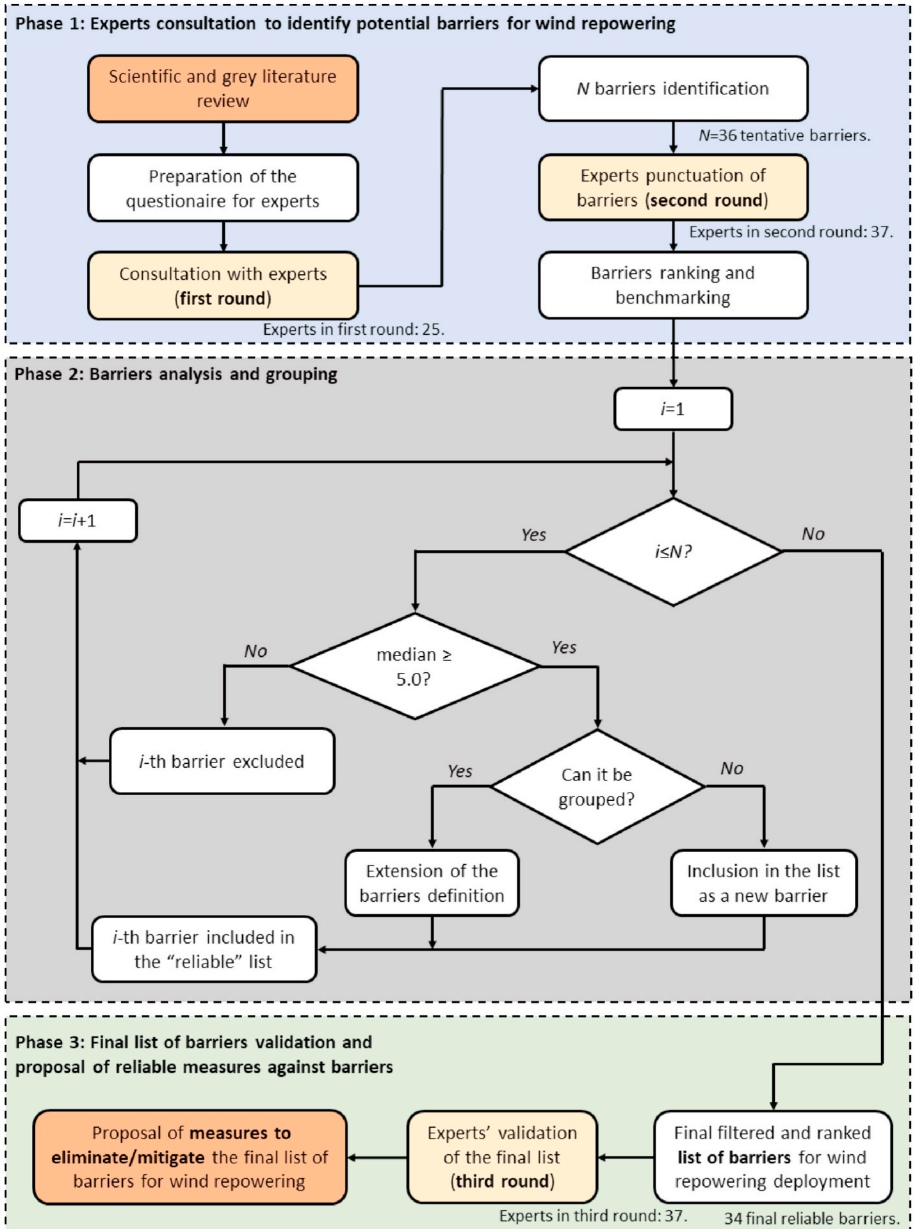

Fig. 2. Flow-chart of the followed process to identify and rank barriers for wind repowering through an expert judgment approach. Own elaboration.

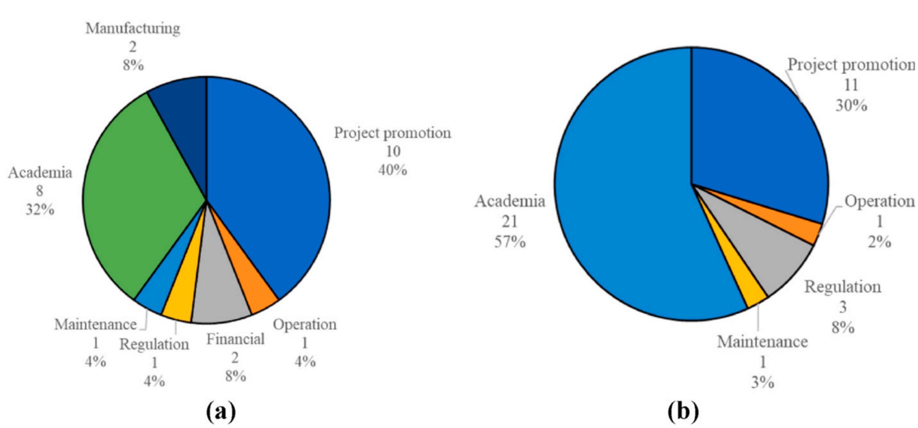

Fig. 3. Composition of the panel of experts: (a) First phase, (b) Second and third phases. Own elaboration.

models (the assumption that improved efficiency is the result of a particular action or the impact, which results from the omission of an action or doing something in a different way) by adding extra open questions based in the taxonomy presented in Ref. [45].

- **Technical barriers:** For this section, we prepared a set of 10 questions focusing on aspects that are not yet clear in the existing literature, that are usually taken as hypotheses, and that can explain discrepancies between published studies and reality. For instance, we asked for the reasoned opinions of the experts on the real useful lifespan of a wind turbine generator, the market trust in secondhand wind turbine generators or the real feasibility of harnessing the existing wind farm infrastructure in full repowering projects.
- **Economic barriers:** In a similar manner to the technical barriers, we asked the experts 6 questions related to economic and market hurdles for wind repowering. In this section, we included questions related to the real affordable operation risk limits or minimum profitability.
- **Social, environmental and regulatory concerns:** Finally, we asked 13 questions related to the social acceptance of wind farms, and the observed real impact of wind farms by the regulators and citizens.

After the first consultation with the experts, we identified a raw set of potential barriers. However, not all these barriers can be considered "reliable", i.e., they cannot be considered significant. Thus, we sent back the raw set of potential barriers to all of the experts and asked them to rank them. They were asked to rank each barrier in a range from zero ("not relevant at all") to 10 ("extremely relevant"). The set of barriers were then classified by categories, which the experts were asked to evaluate the impact of using a three-level scale ("of little relevance", "Rather relevant" or "Very relevant"). In this case, we received a valid answer from 37 experts, whose roles can be seen in Fig. 3 (b). We then analyzed the scores and grouped or discarded the barriers as stated before.

3. Results

3.1. Experts consultation (surveys summary)

Below we summarize the responses provided by the panel of experts to the survey conducted. The list of questions can be found in Appendix A.

3.1.1. Technical and environmental aspects

It is clear that there are still sites with sufficient wind resources. The technological evolution of wind turbine generators means that sites that previously had no relevant wind resources can now be exploited.

The lifespan of a wind turbine is far from approaching a particular value or a closed interval. The experts establish a very wide interval, between 15 and 30 years. They consider it inappropriate to indicate the lifespan of the equipment *a priori* since the quality of maintenance has a great impact on this parameter. The experts also point out that a lifespan cannot even be established in the final phase of a wind turbine's life, as it may be of interest to extend it by utilizing of corrective maintenance techniques. The point made by many manufacturers that they only maintain machine parts after 10 years of operation, should be considered.

The experts stress that extending the useful life of wind turbine generators is the most used option in comparison with full or partial repowering since it does not compromise the generation of short-term profit, which is the parameter most considered by the promoters. They also point out that difficulties and obstacles in administrative management are a major threat both to investment in new wind farms and to repowering. There seems to be a widespread view that a reduction of the bureaucratic burden would better promote this option. A notable response is the option of repowering without having to dismantle the wind farm before implementing the new one, eliminating the loss of revenue during the implementation of the new facilities. It even opens up the possibility of temporarily maintaining the old wind farm and the repowered one.

The majority of the experts consulted believe that new larger wind turbine generators will have a less visual and environmental impact, as the number of wind turbines will be reduced. It is striking that in nearby installations where machines of different sizes coexist, observers have found it difficult to distinguish which wind turbine is larger. From the point of view of the effect on birdlife, the swept area would be the element that generates the greatest probability of an accident. Larger wind turbines have a lower sweep area/nominal power ratio, assuming a smaller effect in relative terms.

Experts claim that the installation of taller machines with larger rotor diameters requires new environmental impact studies, although they insist that the environmental impact is not increased. In some wind farms, repowering would be very complicated because environmental regulations have been modified in recent years.

The developers indicate that they are concerned about possible structural failures in the foundations and blades, mainly caused by material fatigue. Some of them have examined their wind farms through an external audit. They are negatively surprised that life extension audits do not incorporate the study of foundations. This does not mean that the machines will break down after that date, but it does increase the risk.

The power limitation in repowered wind farms allows taking advantage of the existing electrical infrastructures, both for connection and for injection, which makes the investment cheaper. However, facilitating the increase in power leads to a very notable increase in profitability, increasing the efficiency and exploitation options of this type of investment. In any case, although the promoters indicate that this limitation is very relevant, repowering should be studied by limiting power in each case, since in some wind farms it will be more relevant than in others.

Experts note other technical difficulties in dealing with repowering, highlighting: (i) very gusty winds or very extreme weather conditions where it would be less risky to keep wind turbine generators small; (ii) locations where a larger foundation would not be possible; (iii) sites where, extending and correcting access, and new transport restrictions were not possible to overcome or blasting was needed to condition accesses that would completely change the landscape; (iv) locations with highly congested grid connection nodes for existing wind farms; (v) and sites, where increasing the height of the machines, will violate existing spaces and easements, such as military radars, antennas, or airspace areas. In general, respondents indicate that these are not significant obstacles, but they are inherent to each project, although the large size of the machines and accesses are indicated.

The main technical obstacles reported are related to the inability of the power grid to evacuate the energy generated by a reconfigured wind farm if this means an increase in its nominal power. The experts also pointed out other important possible concerns: a wake effect can be generated in the wind turbines of other existing farms outside the reconfigured wind farm; Compliance with grid codes can affect farms connected and not recharged, more specifically voltage control in the steady-state, or the response to dips because many wind turbines do not comply and could create a discriminatory treatment with the TSO (Transmission System Operator), compared to the new ones. In addition, the latest generation of wind turbines may not be adapted to locations with high wind turbine classes and turbulence should be considered, assuming a substantial increase in cost by changing the wind turbine generator class.

3.1.2. Economic aspects

In general, respondents consider that a wind farm that has exceeded half of its useful life and is financially depreciated, even if maintenance costs increase, it is a profitable facility as long as the revenues exceed the costs. Here the experts point out that a detailed study of each wind farm is necessary. The relative assessment that it is the older wind farms that occupy the areas with the greatest wind resource should be highlighted. The analyzed responses indicate affordable limit values for the operation and maintenance costs in the range of € 40,000 and € 45,000 per MW or € 5 to € 10 per MWh. In any case, greater relevance is given to the values related to the profitability of the facility. Respondents indicate a satisfactory turnover 40% higher than all expenses with taxes included.

Most of the promoters surveyed indicate that there is no need for an economic premium to promote wind power plants, only some of them talk about a floor in the price of energy. Some experts refer to remuneration through green bonds or based on CO_2 or efficiency premiums. A minority of experts recommend the reinstatement of the fixed tariff used in compensation systems. When assessing the profitability of repowering a wind farm, the investment must consider the disposal of old wind turbine generators, reduction of power generated during their dismantling and installation, and the energy not sold by the old wind turbine generators (usually considered as the residual value of the old wind farm). These increases in the current investment, in search of better efficiency, would justify a premium to the investment of efficient systems.

On the other hand, according to the panel of experts, several economic measures could be taken to encourage the development of repowering in Spain: allow complete repowering without the loss of the specific remuneration scheme, if it is still in force, at least for the power for which the scheme was granted; establish specific regulations for repowering; establish extensions to the specific remuneration system, or new remuneration mechanisms, for repowering installations according to their age; prioritize access to injection and the reduction of wind turbine generators.

Experts detect a strong investment vocation in markets related to RES. If this investment vocation is not transmitted to real investment, it is due to the high perception of risk justified in the absence of a stable regulatory framework. The risk premium demanded by investors would be greatly reduced in a more stabilized context with rules.

Opinion on the price attractiveness of new wind turbine generators is divided. Some experts indicate that it is not, as can be seen from the fact that repowering projects are very few compared to other countries with similar wind farm portfolios. Others indicate that lower prices would encourage repowering, as is now happening with solar photovoltaics technology.

Regarding the second-hand market of wind turbines, those surveyed do not consider it of interest to acquire a wind turbine that is more than 20 years old, although they would observe its state of maintenance, as well as the expected profitability. The regulatory term that these machines may have, the availability of spare parts and their purchase price (which must compensate for disassembly and transport) is given as data to be considered. In any case, an amount not exceeding € 250,000 per MW is indicated.

3.1.3. Social aspects

The political leaders focus their opinion closer to the disagreement to allow the installation of a repowered wind farm in its backyard, due to two reasons. The first one is that there would be some opposition because of the loss of income for the affected municipalities (taxes, fees, etc.). Secondly, there exist some concerns due to the impact on the fulfilment of objectives with RES established in the European Directives.

As far as local citizens are concerned, it can be assumed that those for whom the installations represent a source of income (rentals, work, etc.) will not agree to their dismantling either. Other citizens would agree for environmental or landscape reasons. In general, citizens disagree with its dismantling, unless the wind farm has had major environmental problems.

In general, it is believed that a new project from a repowered wind farm would be considered more favourable than decommissioning. However, for owners and local entities owning land that is no longer occupied by the new facilities with the repowering, plus the loss of income, the extension of lifespan is easier to accept.

Repowering means generating relevant economic activity, with new investments and taxes, with strong positive local repercussions. It would also mean new income for certain owners, affected by the new installation. The replacement of more problematic wind farms with more efficient ones, with less noise and less damage to the landscape, is also seen as an advantage. Furthermore, there is a view that this must be done for the common good, and that it is politicians who should have the confidence and responsibility to make this type of decision.

Most of the aspects that favor repowering are focused on the generation of secondary businesses to the wind farm, indirect jobs, in addition to income from licenses and taxes, which impact improvements in public sectors.

On the other hand, the main reasons for positioning the public against it may be based on previous experiences of failures to comply with social or environmental aspects, the approach of a project based on larger wind turbines in greater proximity. The loss of income for some landowners by moving the wind turbines, or the inconvenience of the repowering work, is also a negative element.

Citizen opposition and bad past experiences are the main reasons why local politicians do not accept repowering. Possible disputes between neighboring local authorities should also be considered, as some enjoy the income and others suffer the inconvenience.

Experts believe that neither political leaders nor citizens have sufficient information on the role that wind energy plays in total energy production. Similarly, they consider it very commendable that there are still industries in Spain that manufacture wind turbine generators, which generate thousands of direct and indirect jobs, despite no wind turbine generators being installed for several years.

3.1.4. Regulatory and administrative aspects

The surveyed experts agree with there is a complete absence of a specific regulatory framework, which prevents the development of wind technology through repowering. The current regulations consider the repowering of a wind farm in the same way as if it were a new wind farm. However, the current regulations include aspects that favor the installation of fewer, larger, and more efficient wind turbine generators, rather than a larger number of smaller units. The framework, such as the existence of environmental taxes referring to the number of wind turbines. One of the technical aspects that must be considered is the maintenance of access and connection rights to the electricity grid, which experts consider unaffordable if a repowering project is to be considered. The possibility of incentivizing this with a specific public installation concession is also indicated.

The experts indicate that it would be more important to regulate it adequately rather than simplifying it, eliminating intermediaries, such as the current “Single Point of Contact” (and their possible conflicts of interest), giving greater transparency to the whole process, and establishing either validity/expiry periods for access and/or connection permits, or administrative milestones based on the administrative processing of the projects. Most experts indicate that this barrier should be eliminated for the implementation of any type of renewable energy and not only for repowering.

3.1.5. The turning point for repowering

Respondents agree that when institutional support for repowering is considered, that will be the turning point to undertake the repowering of a wind farm. However, some experts have pointed out details that should be considered, such as the moment when spare parts start to fail. Some experts state that the sooner the Administration establishes this turning point to opt for repowering, the more beneficial it will be for the system, because: (i) there is liquidity to invest; (ii) it is profitable to carry out the repowering; (iii) there is no risk on the available resource.

Experts point out that the number of failures in the wind farm leads to large amounts of lost energy and high costs for the corresponding corrective maintenance. Financial experts point out the importance of eliminating uncertainties in order to reduce the risk premium expected by the investor. In the case of allowing an increase in power, the response becomes eminently financial, highlighting as a key parameter the expected yield differential in comparison to the current yield.

The experts highlighted the absence of repowering regulations as the main barrier, as well as the opinion that these regulations would restrict the installations of new wind farms over the repowering of the existing ones. The experts generally agree with: (i) the investment is considerable and thus discouraging when a wind farm is already in operation, highly amortized and in operation without significant problems; (ii) the environmental authorizations are complex to acquire and involves initiating the environmental procedure with a high risk of refusal; (iii) the reordering of land contracts; (iv) the disposal capacity available in the event of an increase in power, as well as the TSO procedures; (v) the possible change of the public concession status of the facility, under the declaration of public utility and (vi) the possible new authorization from the Spanish Air Safety Agency.

3.2. Barrier identification

From the analysis of the answers from the experts, we obtained a list of 36 barriers that are described in Tables 1–5 according to their dimensions (economic, environmental, regulatory, social or technical, respectively). According to the proposed methodology, those barriers were filtered and grouped with the help of the experts in a second round. In this process, only two barriers did not pass the inclusion criteria (E06 and SO05), but as they did not obtain an extremely low score, we decided to retain them in the final list but with concerns.

Fig. 4 shows the scatter box and whisker graphs of the scores given to each barrier by the panel of experts. The graph shows the impact of each barrier, using a scale from 0 to 10 points. We can see that almost all the barriers achieve a moderate-high impact (with average scores ranging from 5 to 6 points), but the regulatory or administrative barriers achieve a significantly higher average score (in the range from 7 to 8 points).

Table 1
Economic barriers. Own elaboration.

ID	Description
E01	The useful life of a generator is a parameter that generates uncertainties in the face of the closure of a wind farm, so that, operators tend to be conservative and prefer to keep in operation the old wind farm instead of repowering.
E02	The low price of old turbines in the secondary market eliminates the residual value of the wind farm and reduces the attractiveness of repowering.
E03	The lack of income during the dismantling process of the old wind farm and the execution of the repowered wind farm intimidates the promoter to repower.
E04	The disappearance of financial obligations after the end of the loan period means that an old wind farm, although inefficient, continues to generate cash flows sufficiently attractive for investors.
E05	Applying low-cost maintenance generates economic benefits that make an old wind farm still profitable in the short term. Moreover, if it comes from an acquisition, it will be financially unfeasible to repower it due to the loss of its real value despite its accounting value.
*E06**	*New wind turbines are too expensive.*
E07	The absence of production premiums reduces the investors' interest in more efficient facilities.
E08	Large electricity companies with participation in the generation side have strategic interests in keeping other power generation plants (gas cycles, thermal plants, etc.) in order to maximize their profitability before their forced decommission. Up to that point, they will offer a barrier to the installation of renewable power.
E09	High penetration of renewable generation sources will inevitably lead to a reduction in prices in the wholesale electricity markets, handing over the “control” of matching the price fixed by non-renewable producers. Currently, there are no mechanisms to set production prices in a high renewable penetration scheme.
E10	Accounting amortization periods are excessively long, and this does not favor repowering due to the great loss of the accounting value that it implies.

Table 2
Environmental. Own elaboration.

ID	Description
ENV01	The visual impact of larger wind turbines is an obstacle to repowering.
ENV02	Other than the visual impact, the environmental damage of larger wind turbines is an obstacle to repowering.
ENV03	Difficult environmental processes reduce the ability of companies to develop large wind farms.
ENV04	The environmental management of the wind farms components and residuals during the dismantling process is difficult to handle and makes it easier to decide to exhaust the lifespan of the wind turbines.

Table 3
Regulatory and/or administrative barriers. Own elaboration.

ID	Description
R01	The Administration does not present clear regulations for the administrative management of repowering projects.
R02	There is no regulatory framework that safely regulates repowering.
R03	The denial of the installation of a new wind farm by the Spanish Aviation Safety Agency.
R04	There are no Government incentives to prioritize investment for efficient systems.
R05	The owners of old wind farms would lose their right of access and connection to the power grid if they develop a repowered wind farm, where the regulations do not consider it necessary.
R06	The Government does not develop specific auctions for wind repowering.

Table 4
Social barriers. Own elaboration.

ID	Description
SO01	The intention, covered under eco-friendly policies, of some political leaders to dismantle wind farms and recover the previous ecosystem blocks repowering in those municipalities governed by green parties.
SO02	The intention of some political leaders to maintain their incomes or fees generated by existing wind farms prevents the development of repowering these wind farms.
SO03	The intention of some citizens to dismantle wind farms and recover the previous ecosystem blocks the repowering in these locations.
SO04	The intention of some citizens to maintain their incomes or jobs generated by existing wind farms prevents the development of repowering of wind farms.
*SO05**	*The latest generation wind turbines reduce the need for labour and cause the concentration of maintenance companies in larger cities, depopulating rural areas.*

In Fig. 4, the experts agree that regulatory and administrative barriers have a significantly higher impact than the others, while the social barriers are less relevant. The majority of barriers show a relatively high dispersion in their values, with the exception of barriers E01, E04, E05, R01 and R02.

On the other hand, Fig. 5 shows in a summarized way the rating dimensions of each group or category of barriers. The vertical axis represents the average rated value of each group of barriers considering the scores given to each barrier included in the category. The horizontal axis shows the average score of each category considering the ratings given by the panel of experts when they were asked to evaluate the impact of each category of barriers on a scale from 0 to 3. Finally, the radius of each point represents the average ranking of the barriers included in the category. As the radius is proportional to the ranking, and the highest impact represents an upper position in the ranking, the smaller the radius, the higher the impact of the category. The background squares show the low impact zone (blue), the rather relevant impact zone (yellow) and the high impact zone (red).

According to Fig. 5, all identified barriers have a significant impact (there are no barriers in the low impact zone). Social, environmental and technical barriers have a moderate-high impact, both as individual barriers and as a category. We must note that technical and

Table 5
Technical barriers. Own elaboration.

ID	Description
T01	There are wind farms in locations where a larger foundation would not be possible, or they have great difficulty in expanding and adapting the pathways, or blasting would be required to condition the pathways to completely change the landscape.
T02	The inability of the grid to evacuate energy at the connection point limits the expansion of wind power repowering in Spain. There are sites with connection nodes to the electricity grid that could become heavily congested if we make an increase in the generated power due to repowering.
T03	The wake effect of the new repowered wind farm will reduce the expected efficiency.
T04	There are locations where an increase in machine height could violate existing spaces and easements, such as military radars, antennas, or airspace restrictions.
T05	The inability of the latest generation wind turbines to adapt to turbulent areas. It is an excessive risk to use last generation wind turbines in areas with high wind gusts or very extreme weather conditions.
T06	The bureaucratic difficulties posed by the existence of single node interlocutors, or intermediary agents between the generator and the electricity grid for the development of repowered wind farms.
T07	As long as spare parts for older wind turbines are available, the investor will not be forced to repower the wind farm.
T08	The structural failure of an old wind farm is considered improbable, so the operator of the wind farm is not forced to propose a complete repowering.
T09	The legislation is too rigid to compute the rated injection power when it considers the installed nominal (rated) capacity of the generators.
T10	There are free sites with sufficient wind resources to guarantee the profitable implementation of a wind farm without the need to eliminate old wind farms.
T11	The absence of traceability in the maintenance of the wind turbine generators and, thus, in the estimation of the remaining useful life of the turbines makes it difficult to sell them in a second-hand market with guarantees, *i.e.*: the remaining lifespan of a "second-hand wind turbine generator" cannot be certified.

environmental barriers show almost the same impact for the experts, according to the three metrics shown in the graph. Undoubtedly, regulatory and administrative barriers have the highest impact, while economic barriers, although they also show a high impact, they unveil more impact as a category (overall impact) than as individual barriers.

4. Discussion

According to the obtained results, we show barriers in all the studied dimensions. The main technical barriers are not related to the technology itself but with the integration in the power system. The experts point out that the restrictions in the capacity of the Point of Connection (PoC) as being one of the main barriers to repowering. Then, we can expect lower improvements of the capacity factor in real projects, which some authors estimate as 7.1% on a per-wind turbine generator basis or 9.7% on a production scale, based on theoretical studies [26]. Furthermore, the expected savings for the utilization of the existing infrastructures in the repowered wind farm, in many cases are not feasible in practice. This is one of the main reasons that made some countries, such as China, overcome some of the existing challenges to repowering by the development of specific energy policies [46]. However, Martínez et al. [47] suggest that repowering is still profitable even when the complete replacement of the power substation and its components is considered.

The technical difficulties are exacerbated by a conservative environmental regulatory framework: promoters fear the complex, lengthy and highly restrictive environmental legalization processes that they must overcome again in the case of deciding to repower a wind farm. Moreover, they can find related social barriers, such as, green parties see new wind turbine generators as more environmentally harmful than older wind turbine generators, although this position has been rebutted by some recent studies, such as [14,17], which show that larger wind turbine generators have lower sweep area/rated power ratio and thus, the disturbance caused to birdlife is not linear. On the other hand, conservative parties can see wind repowering as detrimental to their incomes and taxes (during the decommissioning of the old wind turbine generators and the installation of the new ones) and local jobs (during the exploitation period) due to the reduction of wind turbine generators and their better robustness and digitalization. However, the citizens' environmental concerns to repowering are unclear. In Ref. [47] it is shown that they consider the positive net increase in RES generation in comparison with the environmental impact of the repowered wind farms. Furthermore, for the citizens, the significance of visual impact can be outweighed by a subjective appraisal of larger economic benefits [48].

Regarding the economic aspect, the main barriers are associated with the uncertainty, both on the real useful lifespan of the wind turbine generators, and on the increase of the revenues of the repowered wind farm in comparison with the guaranteed revenues of the existing wind farm in the short term. Most of the surveyed experts state that the real

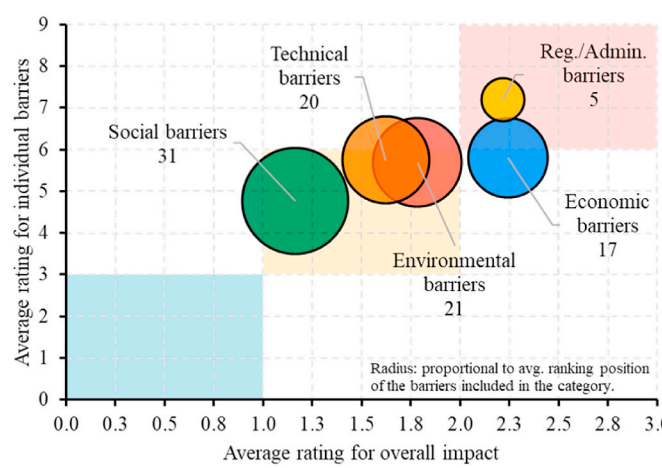

Fig. 5. Rating dimensions for each group of barriers. Own elaboration.

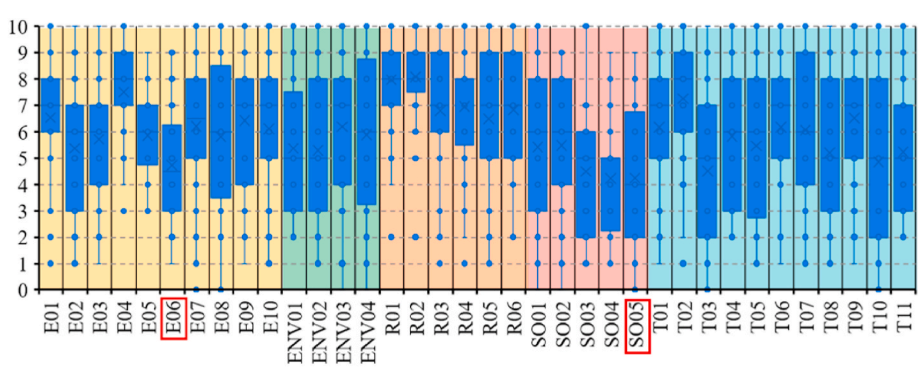

Fig. 4. Results of the barriers scores given by the panel of experts (barriers E06 and SO05 did not pass the inclusion criteria). Own elaboration.

lifespan of the wind farms can be greater than the 20 years estimated by current standards [49] without conducting special extra maintenance actions. This supports the thesis of Rubert et al. [50], who suggest that it can be feasible to extend almost indefinitely the lifespan of a wind farm. We must highlight that the majority of the surveyed agents, and especially the promoters indicate that, they do not feel a need for economic incentives for repowering, in accordance with [40]. This contrasts with the opinion of Ramirez et al. [51], who consider that current RES generators cannot be profitable in most cases without the support of an electricity compensation scheme; or the conclusion of del Río et al. [11], who points out that FiTs and investment subsidies could be particularly appropriate instruments in this case. This can be partly explained due to the general impression of the surveyed agents that new wind turbine generators are not especially expensive and, as pointed out by Zhang et al. [52], the access price of the wind turbine generator is a key factor to determine the profitability of a repowering project. Nevertheless, the panel of experts underlines that some indirect economic incentives may be attractive for investors, such as guaranteed floor prices (to protect investments against the reduction of the average value of the market-clearing prices and the increment of their volatility due to the increase of RES penetration, as also noted in Ref. [53]), green or CO_2 certificates or bonds (also noted in Refs. [54,55]) or efficiency premiums (similarly to those described in Refs. [56,57]). These novel incentive mechanisms agree with the approaches presented in Refs. [52,58].

Last, but not least, the experts agree that the regulatory or administrative barriers are a key to the unattractiveness of repowering. The current regulatory framework results are too unstable for investors who see high uncertainty in the remuneration schemes. Thus, as currently there is absolutely no incentive to increase the efficiency of the exploitation of RES, promoters feel no necessity to modify their facilities. Aligned with what experts have pointed out, Rosales et al. [38] claim that to guarantee the RES development, the simplification of administrative processes is essential. Liao [59] highlights that the reason for the success of some regulatory control instruments is that their role is simple and direct: the Government can simplify administrative procedures and clarify management contents by controlling simplified objectives and matters. However, as remarked by del Río et al. [11], it is recommendable to analyze the role of the different administrative levels in supporting repowering.

Finally, according to the obtained results, we propose a general set of measures to overcome the barriers on each dimension in accordance with the experts' opinions. The proposed measures are briefly summarized in Table 6, but their deep analysis is out of the scope of this work.

The findings of this study need to be considered by taking into account some of the limitations we faced during its creation. The main one has been our limited ability to gain access to the appropriate sample size of industrial agents. The composition of the panel of experts in the different phases of the study was shown in Fig. 3. Although we contacted more than 200 agents we only received a positive answer from 25 of them in the first phase, and 37 in the second and third phases. Moreover, project promoters and academic groups were significantly larger than the other groups of agents, which could have contributed to an undesired selection bias. This fact has a mid-low impact in the identification of barriers, but could be relevant in the second part of the study: the barriers benchmarking. To overcome this limitation, we propose to replicate this study with a larger and more equilibrated sample size of agents, maybe with the help of a public survey institution.

Table 6
Tentative measures to overcome the main barriers to wind repowering in Spain. Own elaboration.

Barriers	ID	Proposed measures
Economic barriers		
E01, E02	M01	Make mandatory a technical audit for wind farms to certificate the true on-field efficiency and the remaining useful life of the wind turbine generators.
E02, E03, E04, E05, E10	M02	Enable a specific economic scheme to support specifically the repowering of wind farms and/or their hybridization (with the same or other technologies).
E04, E05, E06, E07, E08, E09, E10	M03	Promote the efficiency of RES facilities through premiums and/or simplified administrative processes.
Environmental barriers		
ENV01, ENV02	M04	Consider in the environmental impact studies the non-linear relationship between the environmental impact and the increase of the generation capacity.
ENV03, ENV04	M05	Include as a positive environmental impact the increment of the efficiency of the exploitation of the natural resources.
Regulatory and/or administrative barriers		
R01, R02, R03, R05,	M06	Simplify administrative processes for repowering projects, taking into account the authorizations of the original wind farm.
R01, R04, R05, R06	M07	Develop an administrative management procedure for repowered wind farms, including specific quotas in RES auctions.
Social barriers		
SO01, SO02, SO03, SO04, SO05	M08	Conduct special information campaigns and courses for citizens and local leaders (especially those from high resources areas) about the repowering benefits.
SO01, SO02, SO03, SO04, SO05	M09	Raise awareness in society and the political class that not repowering feasible wind farms means inefficient exploitation of the RES and a loss of incomes and development opportunities.
SO01, SO02, SO03, SO04, SO05	M10	Include local leaders and citizen communities in the decision-making processes for the deployment of new WFs.
Technical barriers		
T01, T02, T03, T06, T07, T09, T10	M11	Update the technical requirements and grid codes that must fulfil wind farms promoting repowering projects.
T02, T03, T06, T07, T09	M12	Set a maximum injection power limit for the effective power of the installed wind turbine generators, instead of the in-plate rated power of the generators.
T04	M06	Simplify administrative processes for repowering projects, taking into account the authorizations of the original wind farm.
T07, T08, T11	M01	Make mandatory a technical audit for wind farms to certificate the true on-field efficiency and the remaining useful life of the wind turbine generators.

5. Conclusions

After a deep analysis with the help of a multi-agent panel of experts of the existing barriers to wind repowering in Spain, we can conclude that:

a) There exists a blocked potential for wind repowering in Spain not due to technical or direct market limitations, but mainly due to regulatory or administrative barriers. Non-repowered wind farms mean a lack of exploitation and the efficiency of wind energy resources in the regions.
b) The current limitation of the capacity of the PoC (which is fixed to the rated power of the installed wind turbine generators and not to the effective power) is the most significant technical barrier.
c) A real useful lifespan of the wind turbine generator is larger than expected and by standards added to the uncertainty and volatility of the power markets with high RES penetration, is the main economic barrier. Moreover, the absence of efficiency incentives for these installations makes it unattractive in the repowering decision for promoters.

d) Environmental barriers show mid-high impact, similar to technical barriers. However, environmental concerns are not clear and, in some cases are related to conflicting social concerns. These can be overcome with better information to the society.

The conducted barriers analysis can be extended to other countries and regions with similar conditions regarding wind energy. Furthermore, as Spain was a pioneer in the wind energy field, it faces the repowering decision significantly earlier than other countries. Thus, its experience can be used in accordance. Furthermore, the proposed methodology can be extended to other generation technologies, such as solar photovoltaics. The early barrier identification for the deployment of any technology helps to define better regulatory frameworks and more efficient incentives schemes, where necessary.

This work focuses on identifying the barriers to repowering and the proposal of a general framework of measures to overcome them in a tentative manner. Further studies must analyze in deep the feasibility and impact of these proposed measures.

Credit author statement

Miguel de Simón-Martín: conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, review & editing. **Tomás Ciria-Garcés**: conceptualization, Investigation, Formal analysis, Writing – original draft. **Enrique Rosales-Asensio**: methodology & supervision. **Alberto González-Martínez**: conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, review & editing.

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.

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Appendices.

Appendix A

The survey for the panel of experts contained the following questions:

Q1*: In your opinion, what is the real useful lifespan of a wind turbine?*
Q2*: Among the three alternatives presented in the definitions section (full repowering, partial repowering or extension of the useful life), which is the most attractive option? Why?*
Q3*: Do you consider the visual and environmental impact to a greater or lesser extent between a large set of small-sized wind turbines or a small set of larger (diameter) wind turbine generators?*
Q4*: Do you think that a wind farm that has exceeded half of its useful life is still sufficiently profitable today? Why?*
Q5*: Up to what age of a second-hand wind turbine generator would you consider buying it in a secondary market?*
Q6*: What would you consider to be the limit that you would be willing to pay for the operation and maintenance costs of a wind farm?*
Q7*: In your opinion, are there any technical obstacles to the development of complete repowering in Spain? Please indicate, in order of importance, what these obstacles are?*
Q8*: In your opinion, are there non-technical obstacles (economic, social or regulatory) for the development of full repowering in Spain? Indicate, in order of importance, what these obstacles are?*
Q9*: From the social point of view, do you think that citizens and local political leaders would agree with the dismantling of existing wind farms?*
Q10*: From the social point of view, do you think that citizens and local political leaders would agree to allow the installation of a repowered wind farm in its backyard?*
Q10.1*: What aspects would most influence citizens to favor repowering?*
Q10.2*: What aspects would most influence local administrators to favor repowering?*
Q10.3*: What are the aspects that would most influence against repowering among citizens?*
Q10.4*: What are the aspects that would most influence against repowering among local administrators?*
Q11*: From a technical point of view, do you consider the impact of limiting the injection power to that existing in a wind farm, to be significant?*
Q11.1*: Do you think there are other significant technical limitations? If so, which ones?*
Q11.2*: Do you consider that a simplification of the process of granting energy injection to the grid is necessary?*
Q12*: From an economic point of view, do you consider it necessary to help promote wind power plants? If yes, which model do you consider most appropriate? (Investment subsidy; Remuneration of fixed-rate energy; Fixed premium over the pool; Investment subsidies; Green bonds; Revenues based on saved CO2; Efficiency premiums (German model); Others (specify, please)).*
Q13*: Do you consider that current CapEx and market prices are attractive enough to seriously contemplate a repowering plan? If not, what do you consider the cost they should reach?*
Q14*: From a regulatory point of view, do you consider that the current regulatory framework in Spain strengthens or blocks repowering projects? Why?*
Q15*: Do you think that markets perceive instability in the regulatory system for the future?*
Q16*: Regarding the aspects assessed, what measures do you consider could be taken to encourage the development of repowering in Spain?*
Q17: *In the case of promoting a repowering of a wind farm, do you consider that there are environmental barriers that affect these projects? Do you consider these barriers sufficient to stop the promotion of repowering actions?*
Q18: *Have you assessed the risk of serious or structural failures in wind farms over 15 years old? If yes, which one do you consider is the most worrisome?*
Q19*: Do you consider that there are still sites with sufficient wind resources to guarantee the profitability of a wind farm installation (or do you consider best locations are already occupied by installations)? If yes, why do you think they are not currently exploited?*
Q20*: When do you think it would be the turning point to undertake the repowering of a wind farm? Please, specify briefly your criteria.*
Q21*: When do you think would be the turning point to undertake the full repowering of a wind farm keeping the installed power? Please, specify briefly your criteria.*
Q22*: When do you think would be the turning point to undertake the full repowering of a wind farm with increased installed power? Please, specify briefly your criteria.*
Q23*: Other comments (optional).*

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