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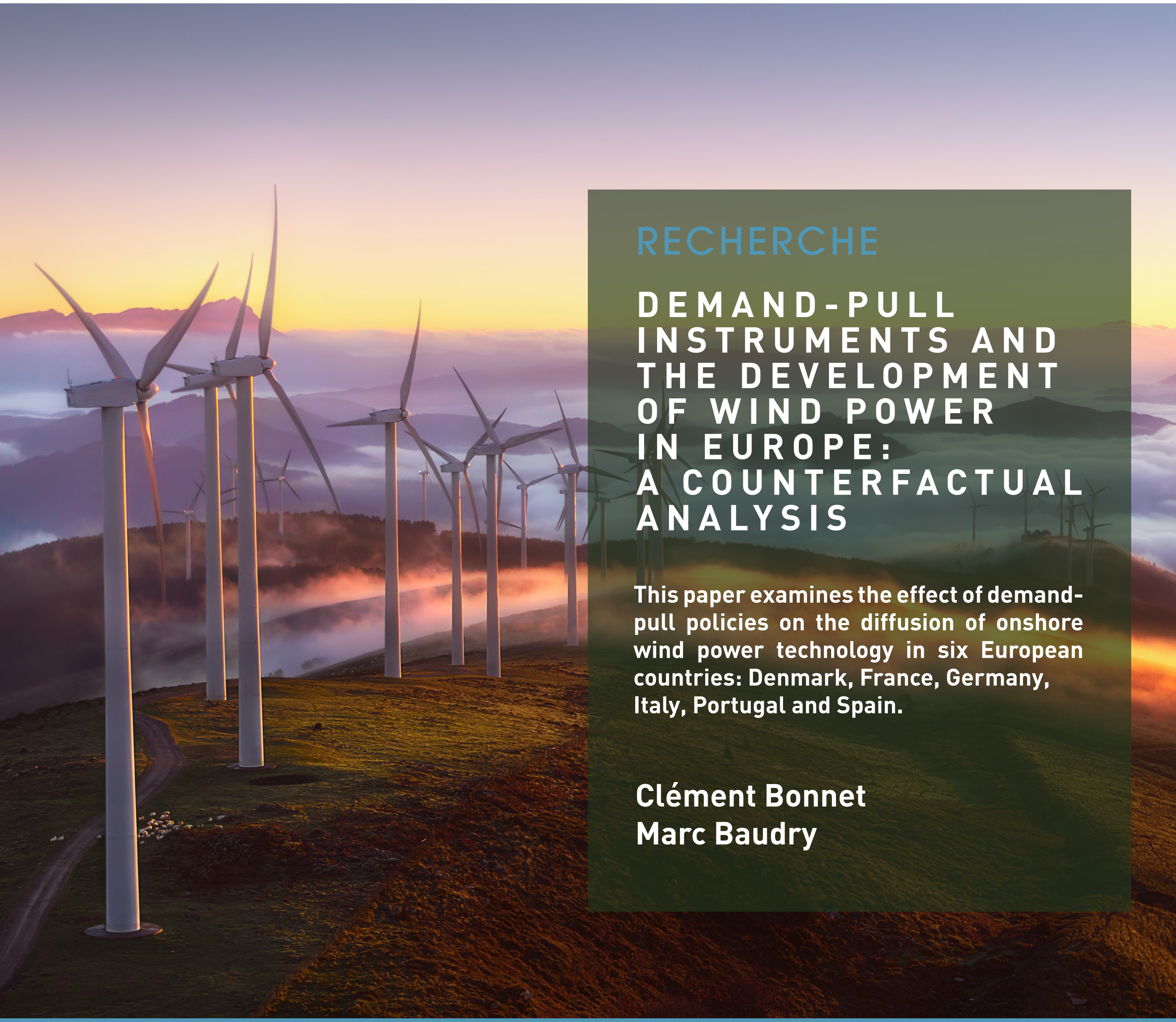

RECHERCHE

DEMAND-PULL INSTRUMENTS AND THE DEVELOPMENT OF WIND POWER IN EUROPE: A COUNTERFACTUAL ANALYSIS

This paper examines the effect of demand-pull policies on the diffusion of onshore wind power technology in six European countries: Denmark, France, Germany, Italy, Portugal and Spain.

Clément Bonnet
Marc Baudry

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Pour toute information complémentaire
For any additional information

Victor Court
IFP School
Centre Economie et Management de l’Energie
Energy Economics and Management Center
victor.court@ifpen.fr
Tél +33 1 47 52 73 17

Demand-pull instruments and the development of wind power in Europe: a counterfactual analysis

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Abstract

Renewable energy technologies are called to play a crucial role in the reduction of greenhouse gas (GHG) emissions. Since most of these technologies did not yet reach grid parity, public policies have been implemented in order to foster their deployment. The approach that has been privileged in Europe is the demand-pull approach that aims at creating a demand for these new technologies and at stimulating their diffusion. This paper examines the effect of demand-pull policies on the diffusion of onshore wind power technology in six European countries: Denmark, France, Germany, Italy, Portugal and Spain. In a first step, a micro-founded model of diffusion is calibrated in order to replicate the observed diffusion of wind power in these six countries. In a second step, a counterfactual analysis is conducted by investigating several scenarios. By taking into account the complex self-sustained dynamics of diffusion and the learning spillovers that operate in the wind power sector, we can derive several insights about demand-pull policies. First, the impact of a demand-pull policy on the diffusion of wind power is determined by the stage at which it comes to support it. The effect seems to be stronger at the beginning of the diffusion. Second, international spillovers do operate in the wind power sector. These international spillovers however are not strong enough to foster the diffusion of wind power in a country having no demand-pull support. We can derive from these two statements that a strategy consisting in not implementing any demand-pull policy, with the expectation that international spillovers will reduce the cost of wind power and foster the diffusion of the technology that then shall become competitive, is not a good option for a country targeting a high share of wind power in its energy mix.

1 Introduction

Promoting renewable energy technologies is a long-term challenge that Europe has to face. However, with the shared dilemma of climate change mitigation European countries managed to implement environmental policies, with varying degrees of efficiency, and emerged as a pioneer in the development of renewable energy technologies. Contrary to regular technologies, the diffusion of environmental technologies is heavily dependent on, among other factors, environmental policies. Indeed, such policies aim to stimulate innovation in this sector by allocating rewards specific to technologies that do not arm the environment and/or penalize pollutant technologies. The support mechanism for renewable energy that has been privileged in Europe is the implementation of demand-pull policies. These policies aim at creating a favourable market for supported technologies in order to foster their deployment. The main policy instruments to enhance a favourable market for renewable energy are feed-in tariffs (FITs), feed-in premiums (FIPs) and green tradable certificates (TGC). FITs are fixed and defined for a given period, usually 10 to 20 years. Coupled with a purchase obligation, they make it compulsory for distributors to buy electricity from renewable electricity sources at a given rate, higher than the market price. In the same idea, FIPs consist of adding a premium to electricity spot price for renewable electricity. Combined with a priority access to the grid and a purchase obligation, renewable energy generators receive the electricity spot price plus the premium. These two instruments are price-based instruments. At the contrary, TGC are quantity-based instruments. A minimum required quota of green electricity, expressed as a share or a fixed amount, must be fed into the grid. The distributors are then entitled to present an amount of green certificates to prove the injection on the grid of the equivalent quantity of renewable electricity. The price resulting from the matching of producers supply and distributors demand for certificates constitutes a financial reward that is added to the market price of electricity when electricity is generated with renewable resources. Although these three instruments are not the only demand-pull instruments[1], they are called demand-pull policies in the reminder of this article.

There is an extensive literature that assesses the impact of demand-pull instruments on the diffusion of wind power technology. Now that electricity generated with onshore wind power is close to grid parity after years of public support, it might prove to be a good study case. Several articles show that there

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[1] A subsidy to investment cost, for instance, is a demand-pull policy in the sense that it increases the demand for renewable equipments.

is a positive relationship between the existence of a demand-pull instrument and the amount of wind power (REF with dummies). Little is known however about the strength of the causal link between the policy instrument and the newly installed capacities of wind power. In this article we conduct an original counter-factual analysis of the deployment of wind power in six European countries (Germany, Denmark, Spain, Italy, Portugal and France). More precisely, the impact of demand-pull instruments is assessed by taking into account the key aspects of the diffusion of a new technology: the learning dynamics that reduce the cost of the new technology for future adopters and the stage reached in the diffusion of wind power; this is made by considering both leader countries (Germany, Denmark and Spain) and laggard countries (France, Portugal and Italy). The main objective of our study is to quantify the amounts of wind power capacity in the six analysed countries that are imputable to their demand-pull policies. To meet this study objective, we proceed in several steps. First, a micro-founded model of diffusion is developed. The model builds on the work of Kemp [35] who proposed to reproduce the diffusion of a new technology by representing the investment decision at the individual level. In the present paper, the investment is more specifically triggered by the expected Return-on-Investment (RoI) of a new MW of wind power capacity which is referred to as the benchmark value of the RoI. Second, we describe how the RoI is computed from a period to another. Both exogenous and endogenous factors affect the level of RoI. An important effort is made to make several variables endogenized, such as the investment cost, the annual output of the wind turbine or the electricity price. Third, the model is calibrated on the basis of the observed RoI and yearly installed wind power capacities in order to replicate, as good as possible, the observed diffusion paths. Fourth, the counterfactual analysis then builds on the causal relation between the dynamics of the profitability and the newly built generation units. More precisely, the payment received by producers under a demand-pull scheme are replaced by the counterfactual values of payment that would have prevailed in the absence of a given policy instrument in order to generate the counterfactual deployment of wind power. Beyond the analysis of the effect of the national policy of each country as if it was isolated, the paper stresses the importance of the interplay between these domestic support policies that benefit from reciprocal spillovers.

The paper is structured as follows. In section 2, we review the literature that assesses the effects of demand-pull policies on the deployment of wind power. The research strategy we follow is detailed in section 3. The presentation of the counterfactual analysis is given in subsection 3.1, the variables that are endogenous to our model are detailed in subsection 3.2 and the geographical and temporal scopes are motivated in subsection 3.3. The micro-founded model of diffusion is presented in section 4. The structure of the model is detailed in subsection4.1 and several key properties of the diffusion process are emphasized in subsection 4.2. Section 5 explains how the profitability index is computed. Subsection 5.1 presents the relations underlying the expression of the RoI, subsection 5.2 details the types of heterogeneity that are synthetized in the index and the calibration of the model is presented in subsection 5.3. Section 6 presents the results from our several scenarios. How the observed diffusion is replicated is detailed in subsection 6.1. Subsections 6.2 and 6.3 investigate the effects of national and foreign policies on the diffusion of wind power in each country. Section 7 discusses our results and section 8 concludes.

2 Literature review

2.1 Demand-pull policy design

Due to their growing cost and to the major role renewable energy will have to play in the energy transition, demand-pull policies have been extensively investigated by researchers. A crucial question regarding these policies is to assess the causal link between a demand-pull instrument and the deployment of the supported technology[2]. Several articles demonstrate the importance of the design of demand-pull schemes. Menanteau et al. compare the efficiency of several incentive schemes for the deployment of renewable energy technologies by taking into account the characteristics of the innovation process and the conditions of adoption [44]. They conclude that, due to the inherent uncertainty of technical change, price-based instruments are more efficient when compared to quantity-based ones. In the same vein, Gross et al. analyse the UK electricity sector and provide several insights about the role of price risk in the design of a support policy to renewable energies [28]. A comparison of the performance of a price-based instrument (FITs) and a quantity-based instrument (TGC) is made by Verbruggen and Lauber [61] on the basis of four criteria: efficacy, efficiency, equity and institutional feasibility. They also conclude that FIT systems perform better than TGC. They underline however how important is the design of the instrument (duration of the support period, level of the tariff,

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[2] It may be thought of as a first step in the comparison of the efficiency of demand-pull policies with that of other economic instruments such as carbon taxation that would also foster the diffusion of renewable energy technologies by increasing the cost of fossil-fueled electricity.

etc.). Focusing on price-based instruments, Couture and Gagnon [11] investigate how investment in renewable energy is influenced by the design of the policy instrument by comparing seven models of FIT schemes.

Several case studies and surveys analyze the effects of demand-pull instruments on the investment in renewable energy technologies. Meyer [46] discusses the demand-pull policies currently in force during the beginning of the 2000s in Germany, in the United-Kingdom, in Holland and in Denmark. Based on this cross-comparison, several proposals are made to guide the implementation of a support scheme at the European Union level. In the same vein, Mitchell et al. [48] compare the renewable obligation scheme implemented in England and Wales with the German FIT. In accordance with the theoretical literature, they show that the price-based instrument is more effective than the quantity-based one in fostering the deployment of renewable energy technologies.

Insights from this literature show that the diversity in policy design and implementation is a crucial element that should be taken into account. This is particularly true with regard to empirical analysis. Moreover, it constitutes a complementary approach that allows assessing the strength of the causal link between demand-pull policies and the deployment of the supported technology. A number of econometric studies attempt to assess this relation in the specific case of wind power.

2.2 The relation between demand-pull policies and the deployment of wind power

Several studies examine the impact of demand-pull policies on the deployment of renewable energy by using dummy variables that represent the existence of a support instrument. By ignoring how demand-pull instruments are designed, this approach is not able to quantify the causal link evoked above but, nonetheless, captures its sign. Menz and Vachon investigate the effects of several state-level policies on the deployment of wind power in the USA (Menz and Vachon, [45]). Their results show that policies based on Renewable Portfolio Standards (RPS) significantly contribute to increase the amount of wind power capacity. In the same vein, Carley evaluates the efficiency of the RPS policy in the US states using a dichotomous variable that captures its implementation (Carley, [10]). The analysis also concludes in favour of a significantly positive impact of the RPS on the total amount of installed capacities of renewable energies. Some studies compare the relative effects of several demand-pull instruments on the deployment of renewable energy by using dummies. Delmas and Sancho compare the effectiveness of Mandatory Green Power Option (MGPO) and RPS in the USA by controlling for natural, social and policy context (Delmas and Sancho, [18]). Dong compares the relative effectiveness of FIT and RPS in promoting wind power (Dong, [19]). Schmid analyzes the effects of FITs and minimum quotas in nine Indian states (Schmid, [55]). A slightly different analysis is conducted by Sarzynski et al. who investigate the impact of state financial incentives, namely cash incentives such as rebates and grants, versus RPS on the market deployment of solar power (Sarzynski et al., [54]). They distinguish the effects of both policies by using cross-sectional time series. Again, both policies are represented by dummies. We argue that these approaches are limited as private investment is determined by profitability, which is directly impacted not by the existence of a support policy in itself, but by the amount of the payment received by the producer of renewable electricity (among other factors, such as the duration of the support, the technological context, etc.).

Finer analyzes are made possible by including more information about both the demand-pull instrument and the techno-economic context in which investments are made. In this vein, Smith and Urpelainen estimate the causal effect of FITs on renewable electricity generation in 26 industrialized countries and demonstrate the effectiveness of this instrument (Smith and Urpelainen, [57]). Popp analyzes the decisions to invest in several low-carbon energy technologies across 26 countries over the 1991-2004 period. His work focuses on testing the impact of technological change on renewable energy deployment. Several other explanatory variables are nonetheless included such as the FIT rates (Popp, [52]). Hitaj et al. estimate the impact of the German FIT on the deployment of wind power capacities (Hitaj et al., [31]). They control for the windiness of sites location and the scarcity of transmission capacities and conclude that the FIT policy has been a significant driver of wind power deployment in Germany. In the same vein, Hitaj assesses to what extent demand-policies have contributed to increase the deployment of wind power in the US by including in the analysis both federal and state level policies such as tax credits, sales tax incentives and other production incentives; the latter being the most cost-effective according the authors conclusions (Hitaj, [30]).

Another approach is to include in the empirical framework a measure of the profitability that allows for a better representation of the investment decision at the micro level. The economic instruments dedicated to the support of wind power and implemented in the EU(15) are assessed by Mulder [50]. To do so, the author uses four different evaluation criteria [3] and examines how they perform in describing

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[3] Tobins Q, Euler equation estimation, investment accelerator model and the effective marginal tax rate.

the patterns of investment in wind power. Mulders conclusions are that the early support of wind power technology allows Germany, Denmark and Spain to better perform, compared to the other European countries. Jenner, Groba and Indvik conduct an econometric analysis that aims at quantifying the causal link between demand-pull instruments and the diffusion of wind and solar power technologies in 26 European countries (Jenner et al., [34]). They take into account several key market characteristics such as the production cost of renewable electricity and the electricity price. The authors use these information to build a profitability index that reflects the investment decision at the individual level. Their work has its limitations however as they consider the cost of generating renewable electricity as exogenous. Moreover, their data comes from the NREL (National Renewable Energy Laboratory) and there is little information about the underlying assumptions of their calculations (e.g. the calibration of the discount rate, of operation and maintenance costs, of the capacity factor...). The authors do not find robust evidence that FITs have driven wind power deployment in Europe. A rather similar analysis can be found in Bolkesjo et al. [5]. They construct a variable that measures the share of the Return-on-Investment from renewable electricity generation that is imputable to demand-pull instruments. They find that these instruments have contributed to increase the deployment of wind power technology. Again, they do not take into account the impact of the technology deployment on the evolution of generation cost. Another article that includes a measure of profitability in an econometric model is Gavard [22]. Using a profit function, the author demonstrates that the main driver of wind power deployment in Denmark, between 2000 and 2010, has been the wind power support policy. The endogeneity of investment costs is not discussed and to our opinion, the results may be biased by the omission of the experience gathered by Danish manufacturers in other markets.

2.3 The nexus of learning, profitability and diffusion

Demand-pull policies are closely related to learning, that is related in this article to adoption externalities as defined by Jaffe et al. [33]. The authors define adoption .Indeed, these policies aim at fostering a decrease of renewable energy cost via adoption externalities that operate during the diffusion of a new technology; they encompass learning-by-doing, learning-by-using and network externalities (Jaffe et al., [33]). Drawing on this, it is relevant to take into account the effect of diffusion on cost decrease when assessing the total impact of demand-pull policies. In order words, it is necessary to incorporate in the analysis both the direct effect of a FIT on the deployment (through the increase of the revenue) and the indirect effect (though the cost decrease that will result from early deployment) on the total deployment of the technology. To our best knowledge, the only paper that deals with this issue is Soderholm and Klaaseen [58]. They use a simultaneous innovation and diffusion model that explains both the decision to invest in wind power capacities and the cost decrease of this technology. The model is estimated using pooled annual time series for four European countries, namely Denmark, Spain, Germany and the United-Kingdom. Learning is modelled with two-factor learning curves that represent how investment costs in a particular country are determined by, on the one hand, the cumulative amount of wind power capacity and, on the other hand, by the public support to R&D in the wind sector. They show that the higher the payment made to producers, the higher is the diffusion rate. They also emphasize the fact that the impact of demand-pull policy will vary depending on the instrument used.

In their article, Soderholm and Klaassen consider that the decrease of investment cost in a particular country depends solely from national factors, i.e. the national cumulative capacity and the public R&D expenses. Nonetheless, this choice is questionable as a body of the literature shows that there are international learning spillovers in the wind sector. Evidence shows that domestic innovation is impacted both by domestic and foreign policies (Dechezlepretre and Glachant, [17]; Grafstrom and Lindman, [25]). Including or not international learning spillovers within a learning curve framework may considerably change the results as shown by Lindman and Soderholm in the meta-analysis they conduct on wind power learning rates (Lindman and Soderholm, [39]). In their view, the fact that investment costs have both an international component (i.e. the turbine) and other country specific components (i.e. the cost of land, the cost of labor) advocates for considering both dimensions when modelling the learning dynamics. As Ek and Soderholm show, investment costs do not have the same learning elasticities with respect to global and national cumulative capacities (Ek and Soderholm, [20]).

Finally, the development of wind power is constrained by the availability of sites suitable for the construction of new wind farms. It seems that this constraint has not received much attention in the literature. Yet, it may have a substantial incidence in the assessment of the impact of policy instruments. Indeed, the impact of a same instrument may depend on the level of development already achieved. Said another way, it defines a potential of full development of wind power similar to that considered in the literature on the S-curve of technology adoption. Building on these elements, we aim at assessing the total effect of demand-pull policies on wind power deployment by taking into account several features of the diffusion phenomenon and the context in which it operates:

- Demand-pull instruments must be expressed in our model in such a way that their main characteristics are explicitly represented (e.g. instrument type, tariff rates, support length, variations over time, etc.)
- Since we conduct a counterfactual analysis in which we test the impact of demand-pull policies, the economic variables that are suspected to be influenced by these policies must be endogenised. This is the case for investment costs, for the cost of capital which is used as a discount rate and the for electricity prices.
- The learning curves should have both a national and an international component in order to take into account potential international spillovers.
- The impact of policy instruments must be contingent on the level of development already achieved to account for the existence of a constraint of availability of sites.

Finally, since there are major uncertainties about the true performance of new technologies, we adopt a framework in which agents do not maximize their profits due to limited information [4]. Instead, agents choose to adopt the new technology when it is profitable. The model is described in section 4.

3 Research strategy

3.1 Counterfactual analysis of wind power diffusion

The empirical analysis of the diffusion of a new technology finds its origins in the pioneering work of Griliches [26] and Mansfield [41]. Originally, it was intended to formally reproduce the S-shaped time path of the rate of diffusion typically observed for many technologies. This analysis is usually said to be holistic as it provides an aggregated representation of individual decisions which are not explicitly analyzed but are assumed to interact through the transmission of information and feedback [5]. If the role of economic and financial incentives was initially disregarded, some authors have sought

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[4] As explained by Winter, the essence of optimization is a thorough surveying of a set of alternatives, accompanied by consistent application of decision criteria. In the probing of an unfamiliar context, the typical situation is that the only alternatives actually available for surveying are a collection of first steps in various divergent directions (Winter, [62]).

[5] The term 'epidemiological' is sometimes used in place of the term 'holistic' in reference to the dissemination of infectious diseases that also follows a S-shaped curve.

to remedy to this weakness (see e.g. [15]; [1] and [2] ; [27]). Usha Rao and Kishore [60] propose a survey of applications of this approach to the case of renewable energy technologies. The approach, however, remains devoid of an explicit representation of a process of rational economic decision.

The micro-founded approach to the diffusion of onshore wind power proposed in this article is inspired by the work of Kemp [35], although it was on a different technology. Unlike the holistic approach, the proposed model details the decision to install a MW of wind power. The investment is assumed to be realized if it is profitable, as measured by a positive average Return-of-Investment per unit of installed capacity (in MW). However, under similar economic conditions, the profitability levels of new investments in wind power capacities are heterogeneous within a same country. This heterogeneity results from differences in terms of climatic conditions, site access, local acceptability and design of the wind farm. This is captured by a distribution of the profitability at the individual level around an average value. The average level of profitability, a position parameter of the distribution, varies among years due to learning effects, turbines scaling and some exogenous factors including demand-pull policies.

The micro-founded model aims at explaining the time path of diffusion of wind power by the variations of the average profitability over time. Hence, the theoretical profitability of a MW of wind power is computed and its variations over time will determine the path of adoption of the technology.

In this study two geographical scopes of learning influence the investment cost of wind power.

First, it is considered that the experience gathered at the European level may lower the investment cost in a country. In other words, there are international learning spillovers across European countries. Second, each country enjoys a national learning from the capacities installed within its borders. Hence, the assumption is made that, for a given country, the conversion of accumulated experience into cost reduction is not the same whether it originates from the national or the regional (i.e. European) levels. Both types of learning react to the cumulative installed capacities of wind power which is considered as a good proxy of the accumulated experience [39]. Contrary to the holistic approach, economic incentives, learning and diffusion are thus tightly linked in the micro-founded model.

Insert Figure 1

The main steps of the assessment method of the impact of demand-pull policies are graphically summarized on Figure 1. It proceeds in two steps. First, the parameters of the micro-founded diffusion model are calibrated in order to replicate, as good as possible, the observed time paths of diffusion of wind power technology in the six analyzed countries. More details about these parameters and the way they are calibrated are given in subsection 5.3. Both the inputs and the outputs of the model are known. The inputs are the payments received by producers, i.e. demand-pull policies and/or electricity price, and some contextual variables that influenced wind power profitability. The outputs of the model are the newly installed capacities. The link from a time period t to the next is made via the impact of the cumulative capacities on the variation of the average profitability level.

In the second step, the same parameters values are retained for simulating counter-factual scenarios. The scenarios investigated in this study are presented in Table 1. The cumulative installed wind power capacity at time t is endogenously determined with respect to profitability that depends on demand-pull policies and consequently influences: (1) the learning that benefits to new cohorts of wind power installations, (2) the average rated power of newly installed turbines that drives its cost and its productivity.

Observed Diffusion ($OD^{country}$)	Parameters are calibrated in order to fit as good as possible the observed national time paths of diffusion. Their values are different for each country. Hence we have six different $OD^{country}$ scenarios.
Unilateral Removal ($UR^{country}$)	Six scenarios are simulated, in which a country unilaterally suppresses its demand-pull support scheme. The impact on the domestic installed capacities and the impact on the other countries can be deduced.
Multilateral Removal (MR^{low} & MR^{high})	MR^{low}: demand-pull policies are simultaneously suppressed in 2001 by the six countries. Hence, producers only receive the electricity market price. The electricity price is assumed to be equal to the observed market price over the analyzed period.
	MR^{high}: Contrary to scenario MR^{low}, the electricity market prices are increased in order to capture the merit order effect.

Table 1: Presentation of the replicated and simulated scenarios.

Comparing the scenarios $OD^{country}$ with the counter-factual scenarios $UR^{country}$ and MR^{low} & MR^{high} allows to quantify the share of wind power capacities that is imputable to demand-pull policies over 2001-2012. Thereafter, we elaborate on how the key variables of the model are endogenized.

3.2 Endogenous variables

As explained in the literature review, a major challenge when one wants to assess the effects of demand-pull policies is to take into account their dynamic effects on the cost of technology. In this regard, investment costs of wind power are made endogenous in our diffusion model. A natural way to do so is to use learning curves that describe how the investment cost decreases with the cumulative installed capacity. This approach is however limited as it assumes a steady decrease of investment cost with the cumulative installed capacity. It lacks realism as the cost of wind turbines has experienced an increase in the 2000s (Bolinger and Wiser, [9]). Moreover, in their simplest form, learning curves cannot represent the peculiarities of wind power technology (e.g. the relation between the size of the turbine and its productivity). A complete description of how we model learning is given in subsection 5.1 and Appendix B. Here, we discuss a crucial feature of our study that distinguishes it from early articles on the subject. Due to the international spillovers that operate both during the innovation and diffusion stages of wind power technology (Dechezlepretre and Glachant, [17]; Grafstrom and Lindman, [25]), it is relevant to consider that wind power investment cost in a particular country is influenced both by national and international experiences. In this article we consider that, on the one hand, the decrease in turbine cost depends on the experience gathered at the European level. Indeed, during the analyzed period[6] most of European turbines were manufactured in Europe (EU-28)[7]. On the other hand, it is clear that some learning occurs during the commissioning stage (Langniss and Neij, [38]). The spatial scope of learning for grid connection and development works, for instance, is predominantly national. Hence a part of the investment cost, namely the balance-of-system and soft costs, that include civil works, grid connection and other capital costs (Blanco, [7]), is suspected to decrease with the national cumulative installed capacity.

We do not consider that demand-pull instruments are endogenous in our model for two reasons. First, the literature is not conclusive on this issue. Indeed, Grafstrom and Lindman [25] conduct a Hausman test to investigate the null hypothesis of endogeneity of demand-pull policies and reject it. Their sample contains eight European countries encompassing those analyzed in the present study, except Portugal. Such a test cannot be implemented in our model because we do not rely on econometrics to obtain the values of parameters but rather use open-loop calibration. Open-loop calibration is preferred to closed-loop calibration because it is more consistent with the counterfactual analysis of the impact of demand-pull policies. Second, by essence, a counterfactual analysis of the impact of

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[6] It should be kept in mind that it is not the cumulative amount of installed capacities in itself that determines the cost decrease, but the rhythm of deployment (Ferioli, [21]). Hence, it is not a problem to approximate the international experience by the European capacities as long as the time profile of wind power diffusion on Europe is similar to the worldwide one, which is the case over the analyzed period.

[7] According to the Eurobserv'ER barometer 2003, 78.9% of the installed capacities of wind power in 2001 were manufactured by 8 European firms.

demand pull policies assumes that these policies are defined independently of other variables included in the model.

In counterfactuals without demand-pull support, it is assumed that producers would have received the electricity market price. It is well known that the growing share of variable energies fed into the grid contributes to lower the spot prices of electricity ([56]; [36]; [29]; [23]; [13]; [12] and [6]). In this extent, when simulating counter-factual scenarios an ideal model would adjust electricity prices in accordance with the cumulative electricity generation. However, this effect is not considered when simulating $UR^{country}$ scenarios as the decision to invest in wind power relies on investors expectations. A reasonable assumption is that investors expect the European electricity markets to be more and more integrated as supported by the European directive 96/92 and the European directive 2003/54 on the European electricity markets. When taken in isolation, the impact of wind power deployment in one country on electricity prices is diluted in the European electricity markets[8]. Nonetheless, this assumption is ruled out when considering that all national policies are jointly removed as done in the two scenarios MR^{low} & MR^{high}. To address this issue two variants are considered. First, the observed prices over the analyzed period are retained in order to estimate the lower bound of what would have been the diffusion of wind power in the absence of demand-pull policies, this scenario is denoted MR^{low}. It is a lower bound as, in reality, it is likely that the prices would have been higher with a lower share of wind electricity fed into the grid. Consequently, investments in new capacities would also have been higher. To tackle this issue the second variant, denoted MR^{high}, follows the same approach with slightly increased electricity prices to estimate the upper bound of the counter-factual diffusion of wind power when demand-pull polices are jointly removed. We follow Ketterer [36] by considering that the electricity spot price has been 1.46% lower for every additional percent of wind power in the total electricity load of a country[9]. Although the study of Ketterer only focuses on Germany, we use this value as a rule of thumbs for the six countries. More precisely, in the scenario MR^{high} it is implicitly considered that wind integration does not impact electricity prices whereas in reality even a lower diffusion of wind power would have induce a decrease of the average electricity prices. These two scenarios allow us to construct an interval in which the 'true' diffusion of wind power in the absence of demand-pull support would have lie.

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[8] This assumption is more fragile in the case of Germany as this country fed large amounts of wind electricity into the grid.

[9] Time series of counter-factual electricity prices are built by increasing by 1.46% the observed price for every percent of wind power in the electricity load.

A third variable that is endogenized in our model is the weighted average cost of capital (WACC), used as the discount rate. The comprehensive description of this exercise is provided in Appendix D. Stated briefly, we follow a methodology inspired by the recent work conducted within the DIACORE project that aims at assessing the impact of demand-pull instruments on the WACC faced by project developers [71]. In the counterfactual scenarios, the country-specific WACCs are adjusted to account for the reaction of the capital structure to the diffusion dynamics and to account for the suppression of the demand-pull instrument.

Finally, it must be underlined that the counter-factual analysis investigates the case of a suppression of financial support in 2001 but cannot dispose from the assumption of priority access to the grid. Moreover, it is difficult to apprehend the time profile of the electricity generation from wind power that determines producers' revenue. Most of the time, windy hours correspond to off-peak hours, preventing wind producers from recovering their fixed costs [4]. In this analysis only yearly average prices are retained for computing profitability.

3.3 Geographical and temporal scope

The choice of the geographical and temporal scope of this study is strongly affected by the availability of the data (especially the investment cost data). Indeed, the availability of the data on Danish investment cost allows us to start the simulation for this country in 1985. For other countries, the simulation starts in 2000 (Spain, Italy, Germany and Portugal) or 2001 (for France). Our analysis stops in 2012 because after this year, Spain and Portugal have ended their support schemes. The six countries that are included in the analysis are considered to be the leaders in the wind power technology in Europe[10].

A major question regarding the diffusion of wind power is the timing of the implementation of demand-pull instruments (Mulder, [50]). By choosing these countries, we are able to compare two profiles. The first profile are the countries that have implemented a demand-pull policy at a early

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[10] Although Italy is included in the analysis while having a TGC system as in the United-Kingdom, we chose however to not include the United-Kingdom despite its important wind power cumulative capacity. Indeed the two systems are very different. The United-Kingdom's system has suffered from major leakages of subsidies in response to the high volatility of the certificate's price. As a result, a high share of the value of the certificates was captured by electricity suppliers through long-term contracts (Carbon trust, [68]). At the contrary, the features of the Italian system made the certificate price less volatile. The scheme is managed by the Manager of Energy Services (GSE) that acts as a price maker on the certificates market and must sell its certificates as a price fixed by law. Moreover, the GSE has the obligation to buy back the unsold certificates. Finally, the average annual revenue earn by wind power generators, per kWh, from selling certificates is known and can be found in the IEAWind reports. Equivalent information is not available for the United-Kingdom.

stage of wind power deployment in order to create a domestic demand for national firms; this is the case of Germany, Spain and Denmark. The second profile are the countries that have been laggards in the adoption of demand-pull policies, missing the occasion to develop a strong manufacturing sector in the wind power technology; this is the case for France, Italy and Portugal[11]. Simulating a suppression of demand-pull policies in 2001 allows us to test whether or not the effects differ depending on the stage the diffusion.

4 The Model

4.1 Model Setting

The model deals with the decision to install one unit of wind power capacity; units of capacity are expressed in MW. The investment is realized if and only if its profitability is positive. Since the level of profitability is heterogeneous across projects we consider that the level of profitability R for a given cohort t follows a two parameters distribution with a partial density function $f(R;\mu_t,\sigma)$ where μ_t is the average Return-on-Investment at time t and σ is the standard deviation. It allows us to capture the heterogeneity of the investment projects without having to collect detailed information project by project. It should be noted that the two parameters do change from a country to another. Moreover, the average level of profitability μ_t will vary in time due to modifications of demand-pull policies, variations of the investment costs and some other factors. The sources of variations of μ_t are detailed in subsection 5.1. The standard deviation σ is assumed to be independent from demand-pull policies so that its value is time invariant. The model intends to explain the diffusion of wind power by the variations of μ_t. An illustration of the effect of such a variation for a given year t is given by Figure 2. It illustrates the case of an increase of the average profitability, so that the distribution of the profitability level shifts to the right.

Insert Figure 2

The general idea of the model is as follows. At the beginning of a given year t, all the MWs that are profitable ($R > 0$) are developed, or have been previously developed. It is expressed as a fraction $1 - F(0;\mu_t,\sigma)$ of the total potential, denoted k_{max} that represents a theoretical upper bound for the

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[11] In 2008, seven firms from Denmark, Germany and Spain have provided the turbines for 94% and 93% of the cumulative installed capacities in Italy and Portugal, respectively. These firms are Enercon, REpower, Gamesa, Vestas, Ecotechia, Nordex and Siemens. All calculations are made using the IEAWind national reports on Italy and Portugal. Data for France is not available.

diffusion of wind power. Assuming an increase of the average profitability between t and $t+1$, so that $\Delta\mu_t > 0$, the newly installed capacities are the difference between the total amount of profitable projects and the projects that were already profitable and consequently already developed. Hence, the capacities that are installed during the year t are $F(0;\mu_t,\sigma) - F(0;\mu_{t+1},\sigma)$. In the case the average profitability decreases from year t to the next year it is assumed that no new capacities are installed.

Expressed as a fraction of k_{max}, the wind power capacities developed during year t may formally be written as

$$\frac{\Delta k_{t+1}}{k_{max}} = \begin{cases} F\left(0;\mu_t,\sigma\right) - F\left(0;\mu_{t+1},\sigma\right) & \text{if} \quad \Delta\mu_t > 0 \\ 0 & \text{if} \quad \Delta\mu_t \leq 0 \end{cases} \tag{1}$$

In practice, the model is implemented in a slightly different way. Indeed, our purpose is to replicate the observed diffusion, as best as possible, by calibrating the parameters of the model in order to realize a counterfactual analysis. The counterfactual analysis relies on an openloop approach to the dynamics of diffusion. In order to be consistent with the data observed at the beginning of the replicated period, two initial conditions have to be satisfied. These two conditions are

$$\frac{F(R_{max};\mu_0,\sigma) - F(0;\mu_0,\sigma)}{F(R_{max};\mu_0,\sigma)} = \frac{k_0}{k_{max}} \tag{2}$$

and

$$\frac{F(0;\mu_0,\sigma) - F(0;\mu_1,\sigma)}{F(R_{max};\mu_0,\sigma)} = \frac{\Delta k_0}{k_{max}}. \tag{3}$$

Condition (2) states that the share of the wind power capacity that is installed at the beginning ($t = 0$) of the period studied amounts to k_0/k_{max}. Satisfying this condition generally requires to truncate the distribution of profitability. Indeed, consider for instance the case of a symmetric distribution of R and a positive value μ_0 of the initial average profitability, which is also the median profitability. Then, more than half of the potential k_{max} would have been already developed at $t = 0$, which is obviously too restrictive. Therefore, we assume that F is truncated to the right by R_{max} so that the profitability does not exceed this level. However, the truncation introduces another unknown parameter R_{max}. We thus introduce the additional condition (3) which states that the share of capacities added during the first period of diffusion studied amounts to $\Delta k_0/k_{max}$. Conditions (2) and (3) can be rewritten as

$$\kappa = \frac{k_0}{F(R_{max};\mu_0,\sigma) - F(0;\mu_0,\sigma)} \tag{4}$$

and

$$\kappa = \frac{\Delta k_0}{F(0;\mu_0,\sigma) - F(0;\mu_1,\sigma)} \tag{5}$$

where $\kappa = k_{max}/\left(F(R_{max};\mu_0,\sigma)\right)$ is treated as a parameter. For known parameters of F, the value of κ is deduced from condition (5) and is sufficient to generate the dynamics of capacities. Indeed, adapting (1) to the truncated distribution yields

$$\Delta k_t = \begin{cases} \kappa\left(F(0;\mu_t,\sigma) - F(0;\mu_{t+1},\sigma)\right) & \text{if} \quad \Delta\mu_t > 0 \\ 0 & \text{if} \quad \Delta\mu_t \leq 0 \end{cases} \tag{6}$$

The value of R_{max} is not required in (6) but it can be extracted from condition (4). In the next subsection the properties of the model are emphasized. Then, section 5 details how the variations of the average profitability are computed.

4.2 Properties of the diffusion process

A first interesting feature of the model is that, if the profitability is initially negative for all capacity units the diffusion process cannot start. This more specifically occurs if R_{max} is negative.

Two factors may trigger diffusion. First, national public policies and their positive effects on the revenue may allow the diffusion to start. Second, an increase of the European cumulative installed capacities, via international spillovers, may lower investment cost. Hence, it takes into account how foreign support policies may contribute to the national deployment of wind power at a national scale.

Another interesting feature is that the diffusion can stop, at least temporarily, before the upper bound of wind power capacity is reached, i.e. before $k_t = k_{max}$. This arises when the expected profitability decreases substantially from a period to the next. It can result, for instance, from a deterioration of economic conditions, from an increase of the prices of metals used to construct wind turbines or from lower public supports. It may follow on from the shape of the distribution of R. Indeed, when many capacities have already been developed, the remaining potential MWs have their profitability level R on the left tail of the distribution represented in Figure 2. Given that the distribution is single peaked, the further they are on the left, the thicker is the tail and, consequently, the smaller is the proportion of new developed capacities for a given translation $\Delta\mu_t$ of the distribution to the right. It follows that the diffusion process is more likely to be stopped due to a decrease of average profitability when many capacity units have already been developed. This sharply contrasts with the holistic approach that is not able to explain why the diffusion process can stop before being completed. In the same idea, the diffusion could be restarted by exogenous shocks that positively affect the profitability.

A last feature that substantially distinguishes the micro-founded model of diffusion from holistic models is that the dynamics of the proportion of developed capacities is led by the variations of the average profitability from year to year. Note that it does not mean that the policy support necessarily needs to increase over time to induce a diffusion of wind power as the learning effect positively affects the average profitability.

5 Variations of the profitability index ($\Delta\mu_t$)

5.1 Modeling the variations of the average profitability

In the model presented in section 4 a key role is given to the average level of profitability μ. The value of this parameter at $t = 0$ is calibrated and what is of interest for us is how its variations affect the diffusion of wind power technology. In order to represent these variations a theoretical level of profitability, denoted $RoI^{\omega}_{c,t}$, is modeled in order to integrate the effects of demand-pull policies, among other effects, on the profitability of wind power. Hence, the variations of μ_t are defined by

$$\Delta\mu_t = \Delta RoI^{\omega}_{c,t}.$$

The average return-on-investment per kWh of generated electricity over a turbine's lifetime for a wind plant installed at time t in country c in a scenario ω is computed as

$$RoI^{\omega}_{c,t} = \frac{Revenue(k^{\omega}_{t-1}) - Cost(k^{\omega}_{t-1})}{Cost(k^{\omega}_{t-1})}. \tag{7}$$

Cohort t represents all wind capacities that have been commissioned at year t and that are affected by the same economic conditions. $Revenue(.)$ and $Cost(.)$ are expressed as functions of the European cumulative capacity k^{ω}_{t-1} at time period $t-1$ in a scenario ω. The specifications of these functions are presented hereinafter and a detailed discussion about how they are constructed is given in Appendix B.

The analysis seeks to investigate the role of demand-pull policies on wind technology diffusion. Obviously, these policies have not only impacted revenue from wind electricity generation. Actually, demand-pull policies have been implemented with the main objective to stimulate wind power diffusion in order to reduce wind electricity cost through learning. Hence, the investment cost for a given year t depends on the cumulative installed capacity at year $t-1$. Learning is thus incorporated in $Cost(.)$ in order to take into account this effect.

At first sight, it can be done by using the simple form of learning curve $C_t = C_{ref}(MW_{t-1}/MW_{ref})^{-\beta}$, where the cost C_t at time t depends on the cumulative installed capacity MW_{t-1} relative to MW_{ref} the installed capacity at the year of reference[12], on an initial cost value C_{ref} and on a learning elasticity β. Hence the learning rate is computed as $1-2^{-\beta}$. Nonetheless, an increase in investment cost has been observed in all the countries considered in this analysis during the mid-late 2000s. Consequently, the analysis would be biased if using a simple learning curve in the counterfactual analysis as the investment cost would mechanically decrease while in reality it has increase. To solve this problem, the main factors responsible for the increase of investment costs have to be incorporated in the learning curve. According to Bolinger and Wiser [9], 58 % of the increase in the prices of turbines in the US between 2002 and 2008 are imputable to turbines scaling and to higher metals prices[13]. Their diagnostic applies to Europe as the majority of the turbines imported in the US between 2002 and 2010 were European (in average, 61% of yearly turbines imports between 2002 and 2010 are from UK, Denmark and the Euro zone; [9]). These two factors are included in the specification of the turbine cost. Other factors responsible for the increase of turbines cost such as labor costs, warranty provisions or profit margins are not considered here as they require hard-to-access data; energy prices are neglected because they only had a small effect. To incorporate the effects of turbines scaling and metal prices the investment cost is decomposed as

$$IC^{\omega}_{c,t} = \left(TC^{\omega}_{c,t} + BOS^{ref}_{c}\right)\left(\frac{k^{\omega}_{national,t-1}}{k^{ref}_{national}}\right)^{-\beta_c}\left(\frac{k^{\omega}_{regional,t-1}}{k^{ref}_{regional}}\right)^{-\theta_c}, \tag{8}$$

where $IC^{\omega}_{c,t}$ denotes the investment cost, composed by the turbine cost ($TC^{\omega}_{c,t}$) and the balance-

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[12] The chosen year of reference does not impact the result, see [21].

[13] When computing these shares, the effects of currency movements are excluded as they just represent the loss of value of the Dollar relative to the Euro.

of-system and soft costs (BOS_c^{ref}). β_c is a national learning exponent and θ_c a regional learning exponent, calibrated to replicate the observed diffusion paths (see subsection 5.3). $k^{\omega}_{national,t}$ represents the cumulative amount of installed capacity at year t within country c's borders. $k^{\omega}_{regional,t}$ measures the cumulative installed capacities in the other European countries (EU-28). Hence we have $k^{\omega}_t = k^{\omega}_{national,t} + k^{\omega}_{regional,t}$. Turbine costs $TC^{\omega}_{c,t}$ is a function that incorporates the effects of turbines scaling and metal prices whereas BOS_c^{ref} takes country-specific reference values that decrease with learning but remain unaffected by other factors.

The specification of $TC^{\omega}_{c,t}$ relies on several equivalence laws between a turbine's mass, its diameter and the corresponding rated power. These equivalences are detailed in Appendix B and allow to express $TC^{\omega}_{c,t}$ in euros/kW as a function of turbine's rated power $Cap^{\omega}_{c,t}$. The turbine cost is written as

$$TC^{\omega}_{c,t} = \left(\sum_{j=1}^{4} w_j \left(\frac{Cap^{\omega}_{c,t}}{Cap_c^{ref}}\right)^{3/2} I_{j,t} + w_{other} \left(\frac{Cap^{\omega}_{c,t}}{Cap_c^{ref}}\right)^{3/2} \right) TC_c^{ref}, \tag{9}$$

with Cap_c^{ref} the initial value of turbine's rated power in country c and TC_c^{ref} the corresponding cost (expressed in euros/kW). The influence of metals prices is captured by the price indexes $I_{j,t}$ that take unit values at the year of reference. Four metals are considered: aluminum, steel, iron and copper. Their weights in the turbine cost, denoted w_j, are calibrated based on their shares in the turbine mass; the conversion from the turbine's mass to its rated power is deduced from the equivalence relations evoked above. Stated briefly, equation (9) applies a correcting factor to the reference value of the turbine cost that captures the effects of turbines scaling and metal prices.

Finally, $Cost(.)$ is written as the discounted sum of all costs, assuming that the investment cost (8) is paid at the first period of operation and that other costs are discounted at rate $a_{c,t}$. Hence, it is written

$$Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1}) = IC^{\omega}_{c,t} + \sum_{i=0}^{T} \frac{Q^{\omega}_{c,t} O\&M}{(1 + a^{\omega}_{c,t})^i} \tag{10}$$

where $O\&M$ denotes the operation and maintenance costs per unit of generated kWh. Due to the lack of data on operation and maintenance costs, they are considered to be time invariant and equal among cohorts and countries. This assumption is made in order to reduce the uncertainty associated with arbitrary chosen country-specific values and the resulting distortions when comparing the levels of profitability. A value of 1.35 euro-cents per kWh is taken as representative because it corresponds to an average estimate based on German, Spanish, Danish and English experiences [77]. Annual amounts of generated electricity are denoted $Q^{\omega}_{c,t}$ and are assumed to be constant over the lifetime of a turbine. $Q^{\omega}_{c,t}$ intervenes both in $Cost(.)$ through the $O\&M$ costs and in $Revenue(.)$. The revenue part of the RoI is computed as the discounted sum of yearly revenue flows:

$$Revenue^{\omega}_{c,t} = \sum_{i=0}^{T} \frac{P^{\omega}_{c,t,i} Q^{\omega}_{c,t}}{(1 + a^{\omega}_{c,t})^{i}}$$

where $P^{\omega}_{c,t,i}$ is the average price at year i paid to a producer of cohort t per generated kWh in a scenario ω. This variable is affected by national demand-pull policies and/or electricity market conditions. The negative effect of turbines scaling on profitability has been incorporated in the $Cost(.)$ function and a consistent representation should also consider its positive effect on turbine's productivity. Again, equivalence laws between wind speed, turbine size and its rated power allow to construct the yearly generated output as a function of turbine capacity. It is written:

$$Q^{\omega}_{c,t} = Q^{ref}_{c} \left(\frac{Cap^{\omega}_{c,t}}{Cap_{ref}}\right)^{\frac{3}{2}\alpha} \tag{11}$$

where Q^{ref}_{c} is the initial country-specific amount of annual output and α is the wind shear exponent. The latter represents the increase in wind speed velocity at higher altitude resulting from a lower effect of obstructions, e.g. buildings or trees. The wind shear exponent is assumed to be equal to one seventh as it corresponds to a smooth and grass-covered terrain. Deviations from these values are captured by the distribution around the level of profitability. To conclude, expected profitability $RoI^{\omega}_{c,t}$ is expressed as a function of turbine's rated power $Cap^{\omega}_{c,t}$ when incorporating (11) in $Revenue^{\omega}_{c,t}$ and $Cost^{\omega}_{c,t}$. It also depends on the cumulative installed capacity at $t-1$ because of the learning effect. It is written

$$RoI^{\omega}_{c,t} = \frac{Revenue(Cap^{\omega}_{c,t}, k^{\omega}_{t-1}) - Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1})}{Cost(Cap^{\omega}_{c,t}, k^{\omega}_{t-1})}. \tag{12}$$

In this expression, the key variable is $Cap^{\omega}_{c,t}$. Data on turbines average rated power are available per year and country in the IEA Wind reports [75]. However, in counterfactual scenarios the average rated power for a cohort t cannot be considered as exogenous as it depends from two factors:

- at the country level, the geographic and climatic peculiarities impact the optimal choice made by wind power plants designers about turbines rated power.

- at the European level, the progress made by manufacturers in producing larger wind turbines positively affects the value of $Cap^{\omega}_{c,t}$.

Consequently, the turbines rated power at time t can be represented by a country-specific function of k^{ω}_{t-1} that approximates the experience gathered by wind turbines manufacturers in building larger units. The European cumulative capacity is chosen instead of the global one in order to exclude the experience gathered by foreign manufacturers, in particular the US and Chinese. According to the European Wind Energy Association, the global market shares of European turbine manufacturers was 37% in 2010 [72]. However, at the European level it rises to 89%. Hence, the European market is a relevant measure of EU manufacturers experience and since k^{ω}_{t} is expressed relatively to the reference level k_{ref} the variation matters, not the absolute level. A functional form of the link between $Cap^{\omega}_{c,t}$ and k^{ω}_{t-1} that fits well the observed relations is

$$Cap^{\omega}_{c,t} = d_c (k^{\omega}_{t-1})^{b_c}, \tag{13}$$

where $b_c < 1$ represents the elasticity of turbines rated power of country c to European cumulative installed capacities. For each country this relation is estimated and the results are presented in the Appendix B. The estimated coefficients are retained when simulating counterfactual scenarios. If suppressing demand-pull policies substantially reduces the diffusion of wind power in a country it will reduce the European cumulative installed capacity and, indirectly, it will reduce the average rated power of the newly built turbines. To summarize, the micro-founded model of diffusion determines the newly installed wind capacities per year for a particular country and consequently determines the value of k^{ω}_{t}, that has two impacts on the variation of the profitability : (1) the learning effect that reduces the installed cost; (2) the growing turbine rated power that increases both the turbine cost and the generated amount of kWh per year. Thus, relation (13) links a period to the next and endogenously determines the diffusion dynamics.

5.2 Sources of heterogeneity and national policies

In this subsection the several types of heterogeneity synthesized by the $RoI^{\omega}_{c,t}$ are detailed. When necessary, precisions are given about the assumptions made for its computation. A complete description of the assumptions and the data used for computing $RoI^{\omega}_{c,t}$ is given in Appendix C.

The first source of heterogeneity is related to demand-pull policies. Among the six countries included in this study, three types of demand-pull policies have been implemented: feed-in tarrifs (FITs), feed-in premiums (FIPs) and tradable green certificates (TGC). Table 2 presents the successive phases of demand-pull support policies analyzed here. A more detailed version of this Table is given in Appendix E. The $RoI_{c,t}^{\omega}$ takes into account the national support policies through the values taken by $P_{c,t,i}^{\omega}$ in $OD^{country}$ scenarios.

	Denmark (1985-2012)	France (2001-2012)	Italy (2000-2012)	Spain (2000-2012)	Portugal (2000-2012)	Germany (2000-2012)
FIT	Phase 1 (1985-1990) Phase 2 (1991-1999) Phase 3 (2000-2002)	Phase 1 (2001-2005) Phase 2 (2006-2012)	Phase 1 (2000-2001)	Phase 1 (2000-2003) Phase 2 (2004-2006) Phase 3 (2007-2012)	Phase 1 (2000-2001) Phase 2 (2002-2004) Phase 3 (2005-2012)	Phase 1 (2000-2008) Phase 2 (2009-2012)
FIP	Phase 4 (2003-2007) Phase 5 (2008-2012)			Phase 1 (2000-2003) Phase 2 (2004-2006) Phase 3 (2007-2012)		
TGC			Phase 2 (2002-2005) Phase 3 (2006-2012)			

Table 2: Evolutions of demand-pull policies for onshore wind power in the six European countries analyzed.

The second source of heterogeneity is technological. First, investment costs are initialized with country-specific values from the IEA Wind national reports [75]. When the reports do not distinguish the turbine cost from other costs the following decomposition is applied: turbine cost is assumed to represent 71% of the investment cost and balance-of-system and soft costs 29 % [7]. Second, learning rates are country specific and capture how the countries convert the experience gathered at the European and the domestic levels into lower investment costs.

The third source of heterogeneity is geographic, which is of special importance for variable energies. First, it is included in the analysis by using national capacity factors. Capacity factors are the ratio between the produced output per year and the maximum theoretical production. Based on Boccard [8], the capacity factors of a MW of wind power is computed for each country. These values are used to initialize the amount of generated output in each country. Then, capacity factors improve with turbines scaling as expressed by (11). Second, geographic peculiarities influence how power plants designers will adapt the optimal size of turbines. For instance, the increase of turbines size in Italy has been slower, compared to other countries such as Germany, in order to adapt the turbines to rough and hard-to-access terrain [75]. Estimates of the link between the turbines rated power and the cumulative European installed capacities capture this second type of geographic heterogeneity.

The last source of heterogeneity is economic. The economic background influences several parameters such as the WACCs, used here as discount rates (see Appendix D), and electricity spot prices. The latter fulfills three functions in the analysis:

- In the case of FIPs and TGCs, a share of producers revenues comes from the electricity market.
- After the scheme ends, if it does before the decommissioning of the plant, the producer only receives the market price.
- In the counterfactual scenarios, the only source of revenue are sales on the electricity spot market. This last point has been detailed in section 3.

These several sources of heterogeneity are included in the model in order to explain the paths of diffusion of wind power technology in the six European countries studied. The diffusion is measured by the **gross** cumulative installed capacities. Indeed, using the net cumulative installed capacities would bias the measure of learning because it would only measure the difference between the total capacities that have been commissioned and those that have been decommissioned. The time series of gross cumulative installed capacities are constructed using several data sources. For Denmark, the data source is the *Master Data Register of Wind Power*. For Germany, Spain and Italy, the data on yearly installed capacities is from the IEAWind annual reports [75]. For France and Portugal, the data is from the website Thewindpower.net that lists all the wind sites that have been developed in these countries.

5.3 Calibration

As already stressed when commenting equation (6), parameter κ is deduced from the other parameters so as to satisfy the initial condition (5). The parameters that must be calibrated are the initial level of average profitability μ_0, the standard deviation σ of the distribution of R, and the two learning exponents θ (European) and β (national). The peculiarity of the counterfactual analysis is that we want to solve the dynamics in open loop, not in closed loop. Indeed, we want to construct a counterfactual time path of the proportion of installed capacities, starting from the same initial conditions than those that have actually prevailed, but proceeding with fictitious values of the revenue earned from wind electricity. For this purpose, we have to make sure that the values used for the parameters enable us to correctly reproduce the time path of wind power deployment in accordance with the actual values of the revenues determined by demand-pull policies. The open loop approach requires to compute the predicted proportion of installed capacities at all dates $t > 0$ on the basis of (6). If the dynamic equation (6) was linear, it could be done analytically and we would be able to estimate the parameters with standard econometric methods. The point is that (6) is highly non linear and that we are not able to find a simple and econometrically tractable analytical expression of Δk_t. Therefore, we calibrate the model rather than estimate it with econometric methods. Notwithstanding, we use a root mean square minimization method to calibrate the parameters. It is done as follows: a grid of possible values of the different parameters is first generated. For each set of parameters' values in the grid, we compute the time path of k_t over the whole period of the study, conditionally on the initial condition (5), and on the observed values of the payments received by producers under support schemes. The set of parameters' values that minimizes the root mean square error (RMSE) between the simulated diffusion and its actual profile is used as the solution. A new minimization, based on a narrower grid with smaller increments between the values of parameters, is implemented until the RMSE obtained for the solution does not decrease more than a fixed relative value. A sensitivity analysis of our results to the parameters of the model is provided in Appendix F. Last but not least, prior to calibrating the parameters we need to specify a distribution function f for R. For the sake of limiting the number of parameters, while allowing enough flexibility, we restrain the analysis to distributions with two parameters, a position parameter μ_t and a dispersion parameter σ. A natural candidate is the Gaussian distribution with expected value μ_t and standard deviation σ. An alternative specification for the distribution of R is the Extreme Maximum Value distribution. This specification is an interesting alternative because it is initially defined for any real value of the return but, contrary to the Gaussian distribution, it is asymmetric. The results of the calibration are presented in Table 3. Among the two distributions of R we investigate, the one with the lower RMSE is retained for conducting the counterfactual analysis. For each country, the lower RMSE is in bold text.

Distribution function of the RoI		DE	FR	IT	PT	ES	DK
Gaussian	μ_0	-9.15	-7.375	-15	-12.135	-3.41	-0.89
	σ	8.75	1.93	4.46	2.92	2.34	0.3375
	β	1.45	0.478	0.38	0.7025	0.95	1.135
	θ	2.34	4.56	1.685	2.285	2.175	0.49
	RMSE	$\mathbf{1.2 * 10^6}$	$1.08 * 10^4$	$1.54 * 10^5$	$1.05 * 10^5$	$\mathbf{3.85 * 10^5}$	$8.76 * 10^4$
Extreme Values	μ_0	-11.17	-3.06	-31.08	-17.515	-2.37	-1.08
	σ	10.65	0.72	1.065	0.595	2.19	0.4
	β	1.5	0.5125	0.196	3.09	0.99	1.585
	θ	2.35	4.35	1.72	2.14	2.251	0.55
	RMSE	$1.22 * 10^6$	$\mathbf{7.58 * 10^3}$	$\mathbf{5.63 * 10^4}$	$\mathbf{7.45 * 10^4}$	$4.06 * 10^5$	$\mathbf{7.20 * 10^4}$

Table 3: Estimation results by country, depending on the distribution function of the RoI (ISO 3166-2 codes are used instead of countries complete names)

6 Results

6.1 Observed Diffusion scenarios ($OD^{country}$)

As explained in section 3 the first step of our analysis is to replicate the diffusion paths of wind power that have been observed. Figure 3 shows, for each country, the observed and the replicated time paths of diffusion (with demand-pull policies). In order to visualize the S-shaped curves of diffusion the time period considered for all countries is 1985-2012; 1985 being the earliest year for which a value of investment cost is available for Denmark. The simulated time path starts later for the other countries (in 2000 for Germany, Spain, Italy and Portugal and in 2001 for France).

Insert Figure 3

Figure 3 demonstrates the ability of the model to replicate the general trends of wind power diffusion in the six countries we study. Although the shapes of the observed and the replicated diffusion are rather similar, there are several jumps in the replicated diffusion that did not occur in real world. This is the case for Germany (2010) and Spain (2008), and more generally for Denmark for which the replicated diffusion is subject to several jumps. This difference between the observed and the replicated deployment is explained by several factors. The first factor is the rise of the prices of metals that began around 2006 and that reaches its maximum, over the analyzed period, in 2009 for aluminum, copper and steel. The higher level is reached in 2012 for iron. Even if we use a three years moving average of the prices of metals, we are not able to perfectly represent how the manufacturers hedge themselves against the volatility of the cost of their inputs. Consequently, the negative effect of the rise of metal prices indexes on profitability, and hence on diffusion, is exaggerated for the years when a shock on metal prices has occurred, until the replicated diffusion catches up the observed one once the price stabilizes.

The second factor are the changes in national demand-pull policies. In Spain and Germany, the jumps in the replicated diffusion occur after a modification of the demand-pull support; in both case it corresponds to an improvement of the profitability through higher payments or longer support periods. In reaction to an improved profitability, the share of newly installed wind capacities rises within a year while actually the administrative process associated with the installation of new renewable energy capacities implies a progressive adjustment. The inability of the model to take into account the administrative process also explains the difference between the replicated and the observed diffusion in Portugal between 2003 and 2006. According to the IEA Wind reports [75], a critical effort has been made during these years, following the Dec.-Law no. 68/2002, to simplify the administrative process concerning the implementation of renewable energy power plants. As it is neglected by the model, all the projects that are considered to be profitable are realized faster than in reality. Finally, the model is able to replicate the general trend of the diffusion in Denmark but it is stair-shaped whereas the observed diffusion is smoother. The flat parts of the curve correspond to periods where no new wind sites should have been commissioned according to the model. However, the period of replication is much more longer than for the other countries and the replication of the general trend gives us confidence in the use of the model for the counterfactual analysis.

6.2 Unilateral Removal scenarios ($UR^{country}$)

The results of the counterfactual scenarios $UR^{country}$ and $MR^{low}\&MR^{high}$ are reported in Table 4. They are expressed as the percentage of difference between the amount of cumulative installed capacities of wind power in 2012 that the model replicates given the actual demand-pull policies and the amount of cumulative installed capacities when a suppression of the support scheme(s) in 2001 is simulated. In other words, the absolute values of the percentages given in this table are the shares of the national cumulative wind capacities that are imputable to the existence of demand-pull support policies between 2001 and 2012, depending on the simulated scenario.

The detailed impact through time of unilateral removals are represented on Figure 4. Replicated diffusion time paths (with demand-pull support) are represented by the dotted lines and the simulated diffusion when support is suppressed in 2001 by the straight lines. Prior commenting this figure, it is

		DE	FR	IT	PT	SP	DK
$UR^{country}$	Country of removal	-37.92%	-94.55%	-88.04%	-74.23%	-48.5%	-24.4%
	Other countries	-28.67	-7.21%	-6.17%	-4.67%	-17%	-1.23%
	MR^{high}	-43.37%	-96.12%	-88.04%	-87.72%	-57.8%	-30.19%
	MR^{low}	-44.62%	-96.36%	-88.04%	-90.62%	-59.32%	-29.24%

Table 4: Differences in % of the cumulative capacities in 2012 between the counterfactual scenarios and the simulated scenarios with demand-pull support (simulations starts in 2001 and ends in 2012).

worthwhile giving some precisions about how the diffusion time paths with demand-pull support are simulated. Compared to the diffusion time paths represented on Figure 3, the dotted lines on Figure 4 are slightly different. Since we take into account the interactions between the six countries when investigating the unilateral removal of their policies, via international spillovers, we do the same when simulating the diffusion time paths with the actual demand-pull policies. Hence, when simulating the observed diffusion, the newly built capacities in each country are jointly determined at each year. To this extent, Figure 4 allows for a finer analysis of the impact of removing demand-pull support. A first remark is that for Spain and Denmark the impact of demand-pull support changes over time. For Spain, removing the support scheme in 2001 has a relatively small impact on diffusion until 2007. Indeed, the diffusion simulated in the absence of demand-pull support is close to the diffusion obtained with support. The disconnection between the two diffusion paths occurs after 2007 when FIPs have been implemented as an option and chosen by 90 % of producers [53]. This modification has been criticized for generating windfall profits but it seems that it has also strongly accelerated the diffusion of wind power in Spain. The same phenomenon is observed for Denmark as the demand-pull support impacts the diffusion only after 2008. Again, it may be explained by a modification of the form of policy support. In Denmark, wind power producers have been helped by a system of premium added to the spot price of electricity until 2008. The total payment was capped to 48 euros/MWh in order to reduce windfall profits while reducing the revenue's volatility. As we consider annual average values of the electricity spot price, this effect is ignored in our model. Since the average electricity price was close to the upper bound of the total payment the effect of the demand-pull support is underestimated before the scheme's reform. The suppression of this cap in 2008 has considerably improved the revenue from wind-generated electricity, as shows the jump in the diffusion process in 2009.

Insert Figure 4

The diffusion paths shown on Figure 4 emphasize how much the temporal dimension is important in determining the strength of the causal link between a demand-pull instrument and the newly developed sites. Indeed, the impact of removing the demand-pull instrument in 2001 is strong for laggard countries (France, Italy and Portugal) but much more lower for early adopters (Germany, Spain and Denmark). When simulating the removal of demand-pull policies in early adopter countries in 2001, we aim at assessing the impact of stopping the policy support on a diffusion that has already started. Our results show that wind power diffusion is partially self-sustained in early adopter countries as significant amounts of wind power capacity would have been installed over 2001-2012 in the absence of any demand-pull support. A comparison of the 2012 installed cumulative wind power capacity in the replicated and the UR scenarios shows that 38%, 48.5% and 24.4% of the installed capacity in Germany, Spain and Denmark, respectively, are imputable to the demand-pull policies that have been in vigor between 2001 and 2012. At the contrary the diffusion of wind power in laggard countries is almost fully imputable to their demand-pull support policies. A unilateral removal of these policies in 2001 would have decreased the 2012 cumulative installed capacities by 94.5%, 88% and 74.2% in France, Italy and Portugal, respectively. For France and to a less extent Italy, the diffusion is almost entirely shaped by the policy support as only a very small amounts of wind capacities would have been installed in the absence of demand-pull support over the 2001-2012 period. These observations lead us to conclude that a demand-pull policy may act as a trigger of the diffusion process. Once it is launched however, it seems unnecessary to maintain it as significant amounts of wind power can be deployed due to the self-sustained feature of the diffusion.

The analyze of the UR scenarios allows us to go further. The impact of international spillovers on the diffusion of wind power are examined by quantifying the effect of an unilateral removal on the five other countries in 2001. The results are reported in Table 4. As can be expected strong effects are found for Spain and Germany (two countries with high levels of wind power installed capacities). For Germany, the removal of the demand-pull support in 2001 would have decrease the 2012 cumulative installed capacities in the five other countries by 28.7%. Spain has also contributed to increase the European cumulative capacities as suppressing its demand-pull policy reduces by 17% the 2012 cumulative installed capacities in the five other countries. In this extent, Germany and Spain have bear the cost of the scheme but also contributed to generate important spillovers toward their European neighbours.

6.3 Multilateral Removal scenarios (MR^{low}&MR^{high})

The impacts of a multilateral removal of demand-pull policies in 2001, expressed as the shares of the 2012 cumulative installed capacities that would have not been installed due to the joint removal of the demand-pull policies in the six countries, are given in the two lower rows of Table 4. The impact is detailed country by country and the corresponding diffusion are depicted on Figure 5. Consistent with the fact that an unilateral removal of their policies in 2001 would have had a relatively small impact on their cumulative capacities compared to the other countries, Germany, Denmark and Spain would have been less impacted by a multilateral removal. Nonetheless, the impact is higher when both domestic and foreign policies are removed. The multilateral removal of demand-pull policies in 2001 would have reduced the amount of cumulative installed capacities by approximately 44% in Germany, 58% in Spain and 30% in Denmark. It should be kept in mind that our analysis focuses on six countries of the European Union and consequently, even when jointly removing their support policies, they continue to benefit from the learning in the other European countries. For Italy and France a multilateral removal of demand-pull policies in 2001 almost prevents the diffusion of wind power to start but the orders of magnitude stay comparable with the unilateral removal scenarios. For Portugal, being the only laggard country for which the diffusion shows some resilience in the UR scenario, it is clear that neighbor countries have play an important role. Indeed, the multilateral removal of demand-pull policies reduces the 2012 cumulative installed capacity by 89%, around 15 points more than in the unilateral removal case.

Insert Figure 5

The comparison of the UR and the MR scenarios indicates that the self-sustained feature of wind power diffusion in early adopter countries is not attributable to foreign policies. If it was the case, the 2012 cumulative installed capacities would have been much more lower in the counterfactual MR scenarios, compared to the UR ones. Hence, even if international spillovers do operate and are significant, the domestic learning seems to have had a more important role in the diffusion of wind power in Germany, Spain and Denmark.

Finally an interesting result is the very small difference between the MR^{low} and MR^{high} scenarios, indicating that the merit order effect has a limited impact. Hence, a lower share of wind electricity fed into the grid would have not been sufficient to raise the profitability of wind projects through higher electricity prices and to induce a significant proportion of additional installed capacities. The two scenarios are presented on Figure 5 for each country.

7 Discussion

Our results can be summarized in two statements:

- The impact of a demand-pull policy on the diffusion of wind power is determined by the stage at which it comes to support it. The effect seems to be stronger at the beginning of the diffusion, and tends to decrease through the successive stages of the diffusion process. To this extent, a demand-pull policy is efficient in triggering the diffusion.

- International spillovers do operate in the wind power sector. On one hand, Spain and Germany have contributed, by generating international spillovers, to significantly increase the installed capacities in foreign countries where demand-pull policies were implemented. On the other hand, these international spillovers are not strong enough to foster a significant diffusion in a foreign country having no demand-pull support.

We can derive from these statements that a free-riding strategy is not a good option for a country that targets an important diffusion of wind power. Such a strategy would conduct the country to not implement any demand-pull support, with the expectation that international spillovers will reduce the cost of wind power and foster the diffusion of the technology that then shall become competitive. This scenario does not seem plausible as the demand-pull support has been a necessary condition to trigger the diffusion of wind power.

The importance of creating niche markets at the beginning of the diffusion is described, for the case of wind power, in Jacobsson and Lauber [32]. These niche markets determine the learning process that, in turn, determines the conditions for a wider diffusion of the technology. Consistent with this idea, our results are in line with the article of Mulder [50]; although the framework differs. Mulder analyzes how wind power investments react to support policies in the EU(15). Indeed, the author compares the efficiency of support policies among the EU(15) and concludes that Germany, Spain and Denmark are the top three performers. These countries have implemented policies that have both triggered high average growth rates of investment in wind power and high mean installed capacity over the time period considered. According to the author, this is due to: (1) the combination of policy instruments used by these countries, (2) the early and consistently application of a price-based mechanism to support wind investment. Also in line with our results, the importance of taking into account the learning dynamics to explain the deployment of wind power is emphasized by Soderholm and Klaassen [58]. The estimation of their innovation-diffusion model shows that the major driving force behind the diffusion of wind power is the reduction of investment cost.

Our ability to replicate the observed diffusion, as explained above, is hampered by the existence of administrative processes that may create a lag between economic conditions and effective deployment. We believe that the ability of our model to replicate the overall trends of wind power diffusion is in line with the purpose of our analysis. A finer approach however should take into account these lags in order to determine how much these administrative factors may affect the diffusion. An article by Pettersson and al. [51] compares the wind power planning and permitting procedures in the Nordic countries. They show that the design of the planning system may lead to cost-ineffective diffusion of wind power as it has been the case in Sweden. At the contrary, the diffusion of wind power in Denmark has been strengthened by vertically integrated systems that designate areas for wind power purpose. Another improvement of the model would be to take into account the relation between the dispersion of profitability and demand-pull policies. In this study, the dispersion of profitability is assumed to be unaffected by demand-pull policies and it may be not always true. In Germany for instance, the support policy is designed to partially levelize spatial heterogeneity in terms of windiness (the period during which the maximum tariff is paid to wind producers is extended for less productive sites).

Another limit of our analysis is related to a wider debate on learning curves. A strand of the literature on bottom-up models departs from the usual one-factor-learning curve and includes the role of R&D expenses (e.g. Kouvaritakis et al., [37]). Excluding the role of R&D expenses may lead us to overestimate the learning rates and to miss major differences among countries in terms of R&D policy. There is missing empirical evidence however of the importance of R&D expenses in the diffusion of wind power. Soderholm and Klaaseen shows that R&D expenses have no direct statistically significant effect on wind power investment (Soderholm and Klaassen, [58]). This could be explained by several factors emphasized by Ek and Soderholm [20]. First, they argue that private expenses are not available, contrary to public R&D expenses on wind power. Second, they analyze how public expenses are allocated and conclude that they are directed toward long term R&D projects with higher failure risks, making it difficult to assess their effects on investment costs. This is consistent with the article of Grafstrom [24] in which the author shows that national R&D expenses do not have a statistically significant effect on countries' knowledge stocks. Further research should focus on the inclusion of R&D expenses in the analysis of diffusion, but some preliminary work remains to be done to understand the medium and long-term effects of R&D on diffusion.

8 Conclusion

This paper presents a counterfactual analysis aiming at assessing the causal link between demand-pull support instruments and the diffusion of wind power technology in six European countries. The results highlight the importance of distinguishing between the newly developed wind power capacities that are imputable to demand-pull instruments and those that would have been developed anyway. Two profiles of countries are analysed: leaders (Denmark, Germany and Spain) and laggards (France, Portugal and Italy). Our counterfactual analysis proceeds in two steps. First, a micro-founded diffusion model is calibrated in order to replicate the observed diffusion of wind power in these six countries. Second, several scenarios are investigated to evaluate the impact of demand-pull policies on wind power diffusion. A first set of scenarios explains how the suppression of the demand-pull policy in a country, assuming that the five other maintain their policies, may impact wind power diffusion. Two other scenarios simulate how the suppression of their demand-pull policies by the six countries simultaneously affects wind power diffusion. It should be noted that the diffusion, both at the domestic and at the European levels, interacts with the investment cost in wind power in Europe. This feature implies that countries are all linked together by international learning spillovers.

Two statements are derived from our results. First, the impact of a demand-pull policy is determined by the stage at which it comes to support the diffusion. Indeed, the effect is stronger at the beginning of the diffusion and tends to decrease over time. It demonstrates that a demand-pull policy is more specifically efficient in triggering the diffusion. Second, international spillovers play a significant role in the diffusion of wind power in Europe. More precisely, both Spain and Germany have contributed to significantly increase the installed capacities of wind power in the other countries. It is clear however that these spillovers are not strong enough to foster the diffusion of wind power in a country having no support policy. Based on these two statements, we can conclude that a free-riding strategy is not a good option for a country that targets an important diffusion of wind power.

Our analysis highlights how important are learning effects in shaping the diffusion of wind power technology. To this extent, further research needs to improve our understanding of innovation in the wind power sector. Because innovation is a long term phenomena, such analyses depend on data availability. A major refinement of our analysis would be to include R&D expenses in order to include learning-by-searching, in addition of learning-by-doing, as in Soderholm and Klaassen [58]. This extension would allow enlarging the scope of our analysis by assessing the optimal balance between demand-pull and supply-push policies, while taking into account the interplay between countries.

A Appendix A: List of variables

This appendix contains the Table 5 that presents the list of the variables used in the body of the article.

B Appendix B: The Return-on-Investment function

The average Return-on-Investment, $RoI^{\omega}_{c,t}$, in country c for the cohort of wind plants commissioned at year t is expressed as

$$RoI^{\omega}_{c,t} = \frac{Revenue(k^{\omega}_{t-1}) - Cost(k^{\omega}_{t-1})}{Cost(k^{\omega}_{t-1})}, \tag{14}$$

where k_{t-1} is the cumulative installed capacity of wind power in Europe (EU-28) at $t-1$. All variables that change with the scenario are indexed by ω. This Appendix details how $Revenue(.)$ and $Cost(.)$ are constructed as functions of k^{ω}_{t-1}. Advantages of making $RoI^{\omega}_{c,t}$ a function of the European cumulative capacity are discussed further in subsection 5.1.

B.1 The Revenue Function

$Revenue(k^{\omega}_{t-1})$ is the discounted sum of the yearly revenue of one MW of wind capacity installed at time t in country c. It is computed as

$$Revenue_{c,t}(k^{\omega}_{t-1}) = \sum_{i=0}^{T} \frac{P^{\omega}_{c,t,i} Q^{\omega}_{c,t}}{(1 + a^{\omega}_{c,t})^{i}}.$$

where T is the power plant lifetime, a_t the discount rate, $P^{\omega}_{c,t,i}$ the average annual price of electricity (in eurocents/kWh) during the year i for the cohort t and $Q^{\omega}_{c,t}$ the annual amount of generated kWh. Prices are taken as exogenous by producers and they are impacted by the policy support. Yearly amounts of generated output depend on national wind resources and on turbines' diameter. The latter factor is a key element because a substantial increase in turbines' size has been observed since technology started to diffuse and it has strongly improved wind plants' productivity. It is known that, *ceteris paribus*, the energy captured by a wind turbine scales with the cube of the wind speed:

$$\frac{Q_i^\omega}{Q_{ref}} = (\frac{S^\omega}{S_{ref}})^3,$$

where S^ω measures the mean wind speed that depends on the tower's height. Q_{ref} and S_{ref} are the reference values of generated output and mean wind speed, respectively. As done in Burton et al. [64] and Coulomb and Neuhoff [14] and supported by the correlation represented on Figure 6, the proportionality between a turbine height and its diameter is assumed. Moreover, the relation between the mean wind speed and the turbine size is approximated by an exponential function.

Insert Figure 6

The mean wind speed variation is a function of turbine's height (H), and thus of its diameter (D) given the proportionality:

$$\frac{S^\omega}{S_{ref}} = (\frac{H^\omega}{H_{ref}})^\alpha = (\frac{D^\omega}{D_{ref}})^\alpha \tag{15}$$

with D_{ref} and H_{ref} the reference values ([64]; [14]). α is the wind shear exponent measuring how mean wind speed increases with tower height. Given that energy scales with the cube of mean wind speed using (15) we can write how quantity scales with the diameter:

$$\frac{Q_i^\omega}{Q_{ref}} = (\frac{D^\omega}{D_{ref}})^{3\alpha}.$$

Finally, the link is made with the installed capacity of the turbine, denoted $Cap_{c,t}^\omega$, as it scales with the square of the diameter ([72]). Thus

$$Q_i^\omega = Q_{ref}(\frac{Cap_i^\omega}{Cap_{ref}})^{\frac{3}{2}\alpha}.$$

To conclude, $Revenue_{c,t}(k_{t-1}^\omega)$ depends only on the average rated power Cap_i^ω of the representative wind turbine and some parameters. The link with k_{t-1} is made explicit below.

B.2 The Cost function

$Cost_{c,t}^\omega$ is the sum of the discounted costs and can be decomposed into two components: investment cost, denoted $IC_{c,t}^\omega$, and operation and maintenance cost per generated kWh denoted $O\&M$. The former is assumed to be paid entirely on the first period so that

$$Cost^{\omega}_{c,t} = IC^{\omega}_{c,t} + \sum_{i=0}^{T} \frac{O\&MQ^{\omega}_{c,t}}{(1+a^{\omega}_{c,t})^i}. \tag{16}$$

As explained in the body of the article, $O\&M$ cost are assumed to be constant for every country and cohort. $IC_{c,t}$ is disaggregated into two components: the turbine cost ($TC_{c,t}$) and the balance-of-system and soft costs (BOS^{ref}_c). As made for the *Revenue* function, $TC_{c,t}$ is expressed as a function of turbine's installed power. *Ceteris paribus*, the turbine's cost scales with its mass. Nonetheless, the analysis takes place in a dynamic framework and the factors that contributed to the observed increase in turbine prices during the late 2000s have to be incorporated. According to Bolinger and Wiser [9], the major factors are metal prices and turbine scaling. In order to include metal prices, the variation of $TC_{c,t}$ is decomposed as

$$\frac{TC_{c,t}}{TC_{ref}} = w_{steel}\frac{m^{\omega}}{m_{ref}} I_{steel,t} + w_{copper}\frac{m^{\omega}}{m_{ref}} I_{copper,t} + w_{iron}\frac{m^{\omega}}{m_{ref}} I_{iron,t} + w_{alu}\frac{m^{\omega}}{m_{ref}} I_{alu,t} + w_{other}\frac{m^{\omega}}{m_{ref}}$$

where the w_j denote the shares of the turbine mass (m^{ω}) of metals and other components. The weights are assumed to be constant over time. Metal prices indexes, denoted by $I_{j,t}$, are introduced to represent the evolutions of metal prices over time and they take unit values for the reference year. A common approximation of the relation between turbine mass and its diameter is known as the cube law [64] and stipulates that the mass scales with the cube of turbine's diameter, so that we can write

$$\frac{TC_{c,t}}{TC_{ref}} = \left(\sum_{j=1}^{4} w_j \left(\frac{D^{\omega}}{D_{ref}}\right)^3 I_{j,t} + w_{other}\left(\frac{D^{\omega}}{D_{ref}}\right)^3 \right).$$

As done for the *Revenue* function, using the relation according to which installed power scales with the square of diameter, the turbine cost is expressed as a function of turbine installed capacity

$$TC_{c,t} = \left(\sum_{j=1}^{4} w_j \left(\frac{Cap^{\omega}}{Cap_{ref}}\right)^{3/2} I_{j,t} + w_{other}\left(\frac{Cap^{\omega}}{Cap_{ref}}\right)^{3/2} \right) TC_{ref}. \tag{17}$$

The second component, BOS^{ref}_c is difficult to model as its determinants are less documented. It is assumed that its values depend from both regional and national learning effects impacting the whole investment cost. Hence, investment cost dynamics are initialized with observed reference values and formalized as

$$IC_{c,t} = (TC^{\omega}_{c,t} + BOS^{ref}_c)\left(\frac{k^{\omega}_{national,t-1}}{k^{ref}_{national}}\right)^{-\beta_c} \left(\frac{k^{\omega}_{regional,t-1}}{k^{ref}_{regional}}\right)^{-\theta_c} \tag{18}$$

where β_c and θ_c are the learning elasticities. Finally, the complete form of $Cost^{\omega}_{c,t}$ is obtained by incorporating (18) in (16). At this stage, $RoI^{\omega}_{c,t}$ is constructed as a function of $Cap^{\omega}_{c,t}$ the average capacity of wind turbines built at year t. National time series of $Cap^{\omega}_{c,t}$ are available and it would be possible to use it to estimate the parameters of the model. However, it could not be assumed that these values would have been the same when simulating the counterfactual scenarios because bigger wind turbines were available due to the technical progress made in manufacturing. In this sense, the average rated power of wind turbine at time t is modeled as a function of the European cumulative capacity, k^{ω}_{t-1}, and country-specific estimations are made on the basis of data on historical average wind turbine rated power, available in the IEAwind annual reports [75]. Results of these estimates are given on Figure 7.

Insert Figure 7

C Appendix C: Assumptions and data

C.1 Investment Costs (IC)

According to the IPCC [80], IC_t for an onshore wind plant encompasses the turbine cost, grid connection costs, civil work costs and other costs (transaction costs, land cost, etc.). The cost values used for initializing the dynamics of diffusion come from the IEAwind annual reports [75], except for France where it comes from [67]. They are summarized in Table 6, the year to which they relate is between brackets. Stars indicate the countries for which, in the absence of available data, a decomposition of the investment cost is applied following Blanco [7]: 71% for the turbine cost and 29% for the balance-of-system and soft costs.

C.2 Operation and Maintenance Costs (O&M)

O&M costs gather insurance costs, management costs, repair and replacement costs. However, depending on studies, all or parts of these costs are taken into account. In order to avoid any bias when comparing countries, the choice is made to use the same value for the six countries. Based on [77], a value of 1.35 euro-cents per kWh is chosen.

C.3 National capacity factors

Assumptions about the capacity factor of a wind turbine may vary significantly from a study to another. In this article, the retained values are from Boccard [8] who computes the realized values of the wind power capacity factors for several European countries. They are reported in Table 7. The initial levels of generated output are computed on the basis of these capacity factors.

C.4 Electricity Prices

The liberalization of electricity markets in Europe that began in the 2000s produced an increasing amount of information. Data on the electricity spot price is used whenever it is available. Otherwise, assumptions on the electricity price are made. Sources and assumptions are detailed in this subsection.

Denmark

The Danish system operator (dk.net) provides data for hourly spot price on DK-west and hourly wind generation since 2003. Prices used are the yearly average price weighted by the wind output. Before 2003 and after 2012 we assume a yearly spot price equals to 50 €/MWh.

Germany

Before 2005, we assume a spot price of 30 €/MWh. Based on data from EPEX between 2005 and 2011, yearly average spot prices are calculated. After 2011, we assume a spot price of 49 €/MWh.

France

In France, since 77% of the generated electricity come from nuclear technology the chosen value for the spot price is the price of the Regulated Access to the Historical Nuclear Electricity, i.e. 42 €/MWh. Even if this value was defined in 2010, it is a good approximation of the cost of nuclear electricity that represents the main competitor for wind power.

Italy

Before 2005, IEA Wind reports on Italy provided the yearly average market revenue of wind producers, a useful information for the RoI computation. Between 2005 and 2012 the system operator (Gestore Mercati Energetici) makes available data on hourly spot price. Yearly averages are used. After 2012, a spot price equals to 60 €/MWh is assumed.

Portugal

Fom 2000 to 2006 regulated tariffs are integrated in RoI. After 2006 yearly average spot prices are used, from the OMEL (Operador del mercado Energéticos). Then after 2012, an assumption of 50 €/MWh is made.

Spain

Since 2000 the OMEL communicates price data. Due to the strong convergence between Spanish and Portuguese markets, the same assumption is made about the future spot price of electricity.

C.5 Metal weights and prices

In this paper, it is assumed for simplicity that metals weights are constant over time. For calibration, the values we choose correspond to the average shares of metals for four types of wind turbines presented on Table 8.

D Appendix D: Estimating the cost of capital

D.1 Expression of the WACC

The discount rate is approximated by the Weighted Average Cost of Capital (WACC). To do so, we start from the expression of the WACC assuming the capital sources are equity and debt:

$$a^{\omega}_{c,t} = (sd^{\omega}_{c,t})(rd_{c,t}) + (1 - sd^{\omega}_{c,t})(re_{c,t}) \tag{19}$$

where $a^{\omega}_{c,t}$ is the WACC of wind projects in country c at time t under scenario ω. The share of debt in the capital structure is denoted $(sd^{\omega}_{c,t})$, and consequently the share of the equity is $(1-sd^{\omega}_{c,t})$. The cost of debt and equity are denoted $rd_{c,t}$ and $re_{c,t}$, respectively. Both these cost are assumed to be exogenous, although the overall WACC is higher when a demand-pull support is suppressed (see below). The capital structure of the WACC depends on the capacity factor of the wind plant. Indeed, Bean et al. highlight a significant relation between the capital structure of wind power investment and the capacity factor of the developed site using a dataset of 318 Spanish wind farms (Bean et al., [3]). Using the Engauge Digitizer software to retrieve the data, we can deduce the following relation:

$$sd^{\omega}_{c,t} = -0.16 + 2.57 * CF^{\omega}_{c,t} \tag{20}$$

with $CF^{\omega}_{c,t}$ the capacity factor of the representative wind plant. Considering the vast experience Spain has with wind power, relation (20) is considered to be valid for the six countries of our sample. The advantage of this approach is to link the capital structure to the evolution of the technology, as the capacity factor evolves all along the diffusion (see Appendix B for a description of the relation between the generated output from a representative wind site and the diffusion of the technology). Indeed, the capacity factor is simply the ratio between the generated output $Q^{\omega}_{c,t}$ and the maximum theoretical production of the site. Hence, we can rewrite the capacity factor as

$$CF^{\omega}_{c,t} = \frac{Q^{ref}_{c}}{8760 * 1000} \left(\frac{d_c(\kappa^{\omega}_{t-1})^{b_c}}{Cap^{ref}_{c}} \right). \tag{21}$$

Incorporating (21) in (20), and (20) in (19), we obtain an expression of the WACC in which parameters vary across countries and the evolution of the WACC, through the changing capital structure, is determined by the rhythm of diffusion of wind technology at the European level. As the cumulative installed capacity grows in Europe, the share of the debt tends to increase making the WACC lower *ceteris paribus* (indeed, the cost of debt is lower than the cost of equity).

D.2 Data sources for the computation of the WACC

D.2.1 Cost of debt

The methodology we follow to compute the costs of debt and equity is rather similar than in the DIACORE report [71]. The cost of debt is modeled by adding a risk premium to a term swap rate in order to represent the behavior of the credit sector[14]. The debt cost is written

$$rd_{c,t} = TS_t + CR_{c,t} + PS,$$

with TS_t denoting the term swap interest rate. The country risk premiums $CR_{c,t}$ are computed as the differences between the average 10-year national government bond interest rates of the country c at time t and the respective rate of German bond. Finally, the project spread that captures the risk component related to the risk of a wind power project is denoted PS. It is assumed to be time-and-country-invariant and equal to 3%, following the DIACORE project assumption [71].

20-year swap rates are rates paid to exchange floating interest rates with a fixed interest rate, namely the LIBOR, with maturity of 20 years, being the assumed temporal horizon of a wind power project. The data is taken from the Federal Reserve Bank of St.Louis website. Data is only available for the 2000-2012 period. As we start to replicate the diffusion of wind power in Denmark by starting in 1985, the swap rates are indexed on the German government bonds for the 1985-2000 period. The government bond rates are available on the Eurostat website. The series used for our computations are the EMU convergence criterion bonds yields.

D.2.2 Cost of equity

The cost of equity is computed with a single factor Capital Asset Pricing Model (CAPM) that describes the relation between the equity cost, the risk free rate denoted RF_t and the market risk premium denoted $MRP_{c,t}$. The relation is expressed as

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[14] See the Annex C of the DIACORE report for a discussion on the computation of the debt cost and the Appendix B for the equity cost (DIACORE, [71]).

$$re_{c,t} = RF_t + beta_c(MRP_{c,t})$$

The proxy of the risk-free rate is the German bonds rate, taken from the Eurostat website. Data on market risk premiums are collected on the 'Market-risk-premia.com' website maintained by Fenebris. Finally, the $beta_c$ measure the stock's relative volatility or, in other words, how the price of a particular stock varies relatively to the price movements of the market as a whole. The betas are calibrated by taking the values of the DIACORE report [71]. The estimation procedure is described in the Table 7 of the Appendix B of the DIACORE report[15].

D.3 Counterfactual WACC

The cost of equity and the cost of debt are considered to remain unchanged in the counterfactual scenarios. As said above, as the capital structure is endogenized it is determined by the diffusion path of wind power technology. Nonetheless, in order to take into account the fact that a stable policy environment reduces the cost of capital the WACC is majored by X% in the counterfactual scenarios depending on the policies that countries have implemented. For instance, German wind producers have benefited from a stable FIT over several years. This stability has reduced the WACC and in a counterfactual situation, it would have been higher in the absence of the demand-pull instrument. Based on the survey conducted within the DIACORE project, we consider that the WACC is majored by X% in the counterfactual scenarios. The values taken by X are the following:

- when the counterfactual scenario simulates the suppression of a FIT, the WACC is majored by 1.25%.
- when the counterfactual scenario simulates the suppression of a FIP, the WACC is majored by 0%, as the electricity market risk remains identical in both scenarios. The same is assumed for the Italian case, as the risk from the certificates market was almost nonexistent due to the role of the regulator (see footnote 10).

E Appendix E: Evolution of the demand-pull schemes in the six European countries

Table 9 presents the several phases of the analyzed demand-pull policies.

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[15] The betas are not explicitly given in the DIACORE report. It is straightforward however to deduce the values from the results and the other inputs of the model as they are given in the report.

F Appendix F: Sensitivity analysis

A sensitivity analysis of results with respect to parameters is conducted. It proceeds in the following steps. First, the difference in terms of installed capacities between the replicated diffusion path and the counterfactual one (in the $UR^{country}$ cases) is computed for each year t from 2001 to 2012 in each country c. The difference in terms of installed capacities is denoted Δ_t^c. Second, this exercise is repeated but with one of the parameter increased by 1%. It is denoted $\overline{\Delta}_t^c$. Third, in order to capture the sensitivity of the simulations to the model's parameters these two differences are compared relatively to the installed capacities as computed for the current year in the replicated diffusion path using the parameters initially calibrated. The installed capacities in country c at year t is denoted MW_t^c. The average values are retained to obtain a measure of the sensitivity. More formally, it is written

$$Sensitivity = \frac{1}{12} \sum_{t=2001}^{2012} [\frac{(\overline{\Delta}_t^c - \Delta_t^c)}{MW_t^c}]$$

In Table 10, the values of *Sensitivity* for each country and parameter are given. The case for a negative shock, i.e. -1%, is also investigated.

A low sensitivity of the simulations to the parameters that are not calibrated or estimated (i.e. q, t, $O\&M$ and BOS_c^{ref}) is observed, which is a good point. As can be expected, simulations are generally more sensitive to the parameters for Italy, France and Portugal. It can be explained by the fact that the diffusion of wind power in these countries strongly depends from their demand-pull policies. Finally, two major parameters are those of the distribution of the profitability, σ and μ_0, in the sense that the model is more sensitive to their values. Because investment decisions are made based on a profitability criteria, this higher sensitivity to the parameters of the distribution was expected. To this extent, a precise calibration based on the minimization of the RMSE, as it is done in this paper, strengthens the validity of our results.

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[1] The sources for Denmark are [75], [59], [50] and [76].

[2] Royal Decree 2818/1998 gives the choice to producers between a FiT and a FiP. Since 'an overwhelming majority of RES plant owners chose the market-based price option', according to [65], only the premium option is considered for the IR index computing.

[3] According to the Royal Decree 2818/1998, the FiT is guaranteed for five years. However, it contains a provision guarantying unlimited availability of premiums and therefore, indirectly, automatic renewal of purchase contracts [65]. A survey conducted among 40 renewable energy producers demonstrated the minor role of the uncertainty on purchase contracts renewal [65].

[4] The Average Electricity Tariff (AET) reflects the overall average cost of the electricity system. The level of the AET is decided each year by the government, values can be found in national reports on Spain [75].

[5] To compute the IR index, the premium option is retained since '90% of wind producers have opted for the FIP-support' according to [53].

[6] Cap and floor prices are indexed on the electricity retail price. In 2008, the values were 73.6 €MWh and 87.8 €MWh.

[7] According to the Royal Decree 1614/2010.

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Variables	Description
μ_t	Position parameter of the distribution of the profitability of wind power units (MW) in a country at time t.
σ	Standard deviation of the distribution of the profitability of wind units in a country.
κ_{max}	Total potential of wind power in a country.
$\Delta\kappa_t$	Amount of newly developed wind power units at time t.
κ_0	Initial, i.e. at the beginning of the simulation period, cumulative wind power capacity in a country.
$RoI^{\omega}_{c,t}$	Benchmark level of profitability of a wind unit at time t, in the country c in the scenario ω.
$IC^{\omega}_{c,t}$	Investment cost (euros/kW) at time t, in the country c in the scenario ω.
$TC^{\omega}_{c,t}$	Turbine cost (euros/kW) at time t, in the country c in the scenario ω.
TC^{ref}_c	Initial turbine cost (euros/kW) in the country c.
BOS^{ref}_c	Balance-of-system and soft costs in the country c.
β_c	National learning exponent of the country c.
θ_c	Regional learning exponent of the country c.
$Cap^{\omega}_{c,t}$	Average turbine's rated power at time t, in the country c in the scenario ω.
Cap^{ref}_c	Initial average turbine's rated power in the country c.
$I_{j,t}$	Index of the price of the metal j at time t.
w_j	Share of the metal j in the total weight of a turbine.
$O\&M$	Operation and maintenance costs.
$a^{\omega}_{c,t}$	discount rates in the country c at time t in the scenario ω.
$Q^{\omega}_{c,t}$	Annual output of a wind unit developed at time t in the country c in the scenario ω.
$P^{\omega}_{c,t,i}$	Average price at time i per unit of output generated by a wind unit developed at time t in the country c in the scenario ω.
α	Wind shear exponent.
d_c	parameter of the relation between the turbine's rated power in the country c and the cumulative European installed capacity.
b_c	elasticity of turbine's rated power in the country c and the cumulative European installed capacity.

Table 5: List of the variables of the model.

	DK* (1985)	DE (2000)	FR* (2001)	IT* (2000)	ES (2000)	PT* (2000)
TC^{ref}_c	904.2	825	756.9	738.5	680.8	1004.65
BOS^{ref}_c	369.3	275	309.1	237.5	239.2	410.35

Table 6: Investment costs data (euros/kW of installed power).

Country	France	Spain	Italy	Germany	Portugal	Denmark
Average realized capacity factors between 2003 and 2007	22.3%	24.8%	19.1%	18.3%	22.7%	22.8%

Table 7: National capacity factors for a typical wind power plant.

	Steel	Iron/Cast Iron	Copper	Aluminium
Vestas V82	70	13	1	1
Gamesa G8X	74	15	2	0
Vestas V80	81	8	1	1
Vestas V112	66	18	1	1
Weights	72.75	13.5	1.25	0.75

Table 8: Metals weights, from [9] (in % of turbines' masses).

	Denmark [1] (1985-2012)	France (2001-2012)	Italy (2000-2012)	Spain (2000-2012)	Portugal (2000-2012)	Germany (2000-2012)
FIT	Phase 1 (1985-1990) 85% of the Local Retail Price (LRP), taxes excluded Phase 2 (1991-1999) 85% of the Local Retail Price (LRP), plus 36 €MWh Phase 3 (2000-2002) 58 €MWh for the first 22 000 full load hours. Then, a premium of 13 €MWh is given (lifetime, total payment capped to 48 €MWh)	Phase 1 (2001-2005) 83.8 €MWh for the first 5 years, then from 30.5 to 83.8 €MWh for 10 years depending on the site productivity Phase 2 (2006-2012) 82 €MWh for the first ten years, then from 28 to 82 €MWh for 10 years (depending on site productivity)	Phase 1 (2000-2001) 100 €MWh for 8 years, then 50 €MWh (lifetime). Then, for cohort of 2001 the payment is 124 €MWh for 8 years, then 69 €MWh (lifetime)	Phase 1 (2000-2003) 62.6 €MWh for 5 years [3] yearly adjusted depending on electricity price. Phase 2 (2004-2006) 90% of the Average AET [4] for 15 years, then 80% lifetime Phase 3 (2007-2012) Tariffs are indexed on the retail price and guaranteed for 20 years. In 2008, the payment was 75.6 €MWh	Phase 1 (2000-2001) 60 €MWh for the first 12 years Phase 2 (2002-2004) 82 €MWh for 20 years Phase 3 (2005-2012) 76 €MWh for 15 years, reduced to 74 €MWh after 2007	Phase 1 (2000-2008) 91 €MWh for 5 years. For the following 15 years the payment is adjusted depending on the site productivity. After 2002 the payment decreases annually by 1.5%. After 2004, it becomes 86 €MWh for 20 years with an annual decrease of 2% Phase 2 (2009-2012) The payment is 92 €MWh with an annual decrease of 1%. As in the first phase, producers receive the full payment during 5 years, it is then adjusted for the remaining 15 years
FIP	Phase 4 (2003-2007) Premium of 13 €MWh (lifetime, total capped to 48 €MWh) Phase 5 (2008-2012) 34 €MWh for the first 22 000 full load hours, then 3 €MWh (lifetime)			Phase 1 [2] (2000-2003) 28.8 €MWh for 5 years added to the AET Phase 2 (2004-2006) Premium equals to 40% of the AET, plus 10% if production is sold on the market Phase 3 [5] (2007-2012) Premium of 30.2 €MWh indexed on the electricity price. A cap on the total payment is introduced [6]. In 2011 the premium is reduced by 35% [7].		
TGC			Phase 2 (2002-2005) Elec. price, plus the certificate price (for 8 years) Phase 3 (2006-2012) Support period increases from 8 to 12 years			

Table 9: Summary of the history of demand-pull support policies to onshore wind power in six European countries.

		DE	FR	IT	PT	SP	DK
σ	−1%	0.0017	0.0276	0.0531	0.1429	0.001	0.0025
	+1%	−0.0067	−0.07	−0.2736	−0.2233	−0.006	−0.0047
μ_0	−1%	−0.0144	−0.1192	−0.3383	−0.2682	−0.0146	−0.009
	+1%	0.0093	0.0752	0.0975	0.175	0.0081	0.0064
β	−1%	0.0024	0.014	0.029	0.0154	0.0029	0.0009
	+1%	−0.0014	−0.0082	0	0	−0.0008	−0.0002
θ	−1%	0.0056	0.0517	0.035	0.0396	0.0076	0.0061
	+1%	−0.0053	−0.0495	−0.0213	−0.0398	−0.0066	−0.0061
d_c	−1%	$-4.7892 * 10^{-16}$	$-1.1226 * 10^{-15}$	0	0	$-2.2986 * 10^{-17}$	$-1.4581 * 10^{-16}$
	+1%	$-1.926 * 10^{-16}$	$-1.1223 * 10^{-15}$	0	0	$5.49 * 10^{-17}$	$1.3341 * 10^{-16}$
b_c	−1%	−0.0008	−0.0142	−0.0032	0.002	−0.0021	−0.0022
	+1%	0.0031	0.0234	0.0289	0.03	0.005	0.003
Q_c^{ref}	−1%	0.0018	0.0136	0.0289	0.0171	0.002	0.002
	+1%	0.0004	−0.0052	−0.0032	0.0063	−0.0009	−0.0011
TC_c^{ref}	−1%	0.0002	−0.0043	0	−0.0159	−0.0006	−0.0009
	+1%	0.0013	0.0086	0.0247	0.0171	0.0027	0.0012
$O\&M$	−1%	−0.0056	−0.0313	−0.0058	−0.0098	−0.0048	−0.0023
	+1%	0.0079	0.041	0.0348	0.0461	0.007	0.0033
BOS_c^{ref}	−1%	$1.4674 * 10^{-5}$	−0.0017	0	0	$-8.8891 * 10^{-5}$	$-3.8284 * 10^{-5}$
	+1%	0.0006	0.0059	0.0247	0.005	0.0012	0.0004

Table 10: Results of the sensitivity analysis.

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