Market pull instruments and the development of wind power in Europe: a counterfactual analysis.

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Abstract

Renewable energies technologies are called to play a crucial role in the reduction of greenhouse gas emissions. Since most of these technologies are immature, public policies provide for two types of support schemes: technology push and market pull. The latter aims at creating and stimulating demand for new technologies. This paper assesses the efficiency of market pull instruments for renewable energy technologies in three steps. First, the yearly average Return-on-Investment (RoI) is computed for a typical wind power plant in six European countries over the last decade (it even goes back to 1985 for Denmark). The RoI synthesizes the effects of several economic instruments such as feed-in tariffs, feed-in premiums, tradable green certificates, investment subsidies and reduced tax system. Second, a micro-founded model of diffusion is built to estimate the impact of the RoI on the yearly installed capacity of wind power in each country. This model is based on Kemp [12] and reproduces the S-shaped trajectory observed during the diffusion of a new technology (Griliches [7]). Third, a counter-factual analysis is carried out by coupling the estimated model with several sets of RoI index including or not the economic instruments implemented during the considered periods. The results enlighten heterogeneous effects of market pull schemes among countries. It underlines the crucial role played by instruments design and by the level of the technological diffusion that is reached when they are implemented.

Keywords: Environmental economics, renewable energy, wind power, technology diffusion, public incentives, counterfactual analysis.

JEL Classification: C61, H23, O33, Q4, Q55.

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1 Introduction.

In November 2014, the European Union has reaffirmed its ambition to introduce 27% of electricity from renewable energies in the European electricity mix by 2030. As renewable energy technologies are for the most part not mature yet given their generation costs, their introduction in the energy landscape needs to be supported by public authorities. Indeed, well before the introduction of the European Union Emission Trading Scheme (EU ETS) several European countries had already taken the initiative to implement national policies of renewable energy support. They were both motivated by global warming issues and national-specific issues such as nuclear phase-out and energy independence. Thus, in the late 2000s the vast majority of the European countries had implemented renewable energy support policy [18] with a clear predominance of the market pull approach over the technology push alternative [21], the former aiming at stimulating the deployment of new renewable energy generation capacities. Among renewable energy technologies, wind onshore became a symbol of national ambitions and is frequently considered as one of the major future energy resources. Since wind onshore is close to reach the grid parity and has been supported for many years, it raises the question of the impacts of market pull public policies in term of generation capacities deployment, balanced with the cost borne by the society. In this paper it is proposed to answer the first part of the question by assessing the impact of market pull support policies on the effective deployment of wind power in six European countries (Germany, Denmark, Italy, Spain, Portugal and France). To do so, we proceed in three steps. First, a micro-founded diffusion model is developed. The model finds its origin in the work of Kemp [12] who proposed to model the diffusion pathway of a new technology by representing the investment decision at the individual level. His approach sharply contrasts with the usual holistic one that can be found in the pioneering works on diffusion models of Griliches [7] and Mansfield [14]. In the present paper, the investment is triggered by the expected return-on-investment of a typical wind farm. The heterogeneity affecting the individual expected return-on-investment due to climatic conditions or site accessibility, for instance, is captured by a distribution around the reference total return-on-investment. The micro-founded version of the diffusion model reveals interesting and realistic properties: the need for a public support to impulse the technology diffusion in the case every wind site is unprofitable, the possibility for the diffusion process being stopped before the full deployment is reached, the role of the variation of the return-on-investment from a year to another and the consideration of two channels of learning, technological and non-technological. Second, we describe the methodology adopted to compute the intrinsic reference rate of return-on-investment. This indicator of the profitability reflects a private investment criterion that synthesizes several market-pull economic instruments. Two families of instruments are distinguished: revenue improving instruments on the one hand and cost alleviating instruments on the second hand. Time series of the intrinsic return-on-investment are constructed for the six countries, taking into account the evolutions of both the national public policies of support to wind power, the cost of wind power technology and the national economic conditions. Time series of the intrinsic return-on-investment are also computed for counterfactual scenarios, excluding or not the role of each family of instruments. Third, the model is calibrated for the purpose of the counterfactual analysis. The parameters of the dynamic equation are chosen to correctly reproduce the time path observed with the actual values of the intrinsic return on investment. Then, several counterfactual
scenarios are explored.

2 Methods.

This section presents the methods used in this paper. First, a micro-founded diffusion model is presented and the strengths of this approach, compared to the so-called holistic approach, are emphasized. Indeed, the micro-founded model has relevant properties that provide for better representation of the diffusion process. The micro-foundation relies on the return-of-investment (RoI) of a typical wind site as a trigger of the investment decision. The retained formula and the role of public support instruments on the RoI are then presented, so as the data and the assumptions made for the computation of times series of the RoI. The model is then calibrated, with regards of the RoI historical values in the six countries, to fit as good as possible the observed time path of the wind technology diffusion.

2.1 The micro-founded diffusion model.

2.1.1 From holistic modeling to micro-founded modeling of technology diffusion.

The empirical analysis of the diffusion of a new technology has its origins in the pioneering work of Griliches [7] and Mansfield [14]. 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 that are not explicitly analyzed but are assumed to interact through the transmission of information and feedback. The term epidemiological is sometimes used in place of the term holistic in reference to the dissemination of infectious diseases which also follows a S-shaped curve. If the role of economic and financial incentives was initially disregarded, some authors have sought to remedy to this weakness (see e.g. [5]; [1] and [2]; [8]). Usha Rao and Kishore [20] 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 capacities proposed in this article is inspired by the work of Kemp [12], although it was on a different technology. Unlike the holistic approach, the model proposed details the investment decision at the wind farm level. The decision is assumed to rely on a positive profitability, as measured by the return on investment, of investing. However, for similar economic conditions and similar cumulative installed capacities, individual projects remain heterogeneous in terms of profitability. This is captured by a distribution of individual return on investment around an expected value that is affected by economic conditions, and among them different policy instruments to support onshore wind power, but also affected by a learning effect. Contrary to the holistic approach, economic incentives and learning are thus tightly linked.

2.1.2 Model setting

We consider the decision of investing at the site level. A country is characterized by a set of sites $n \in \{1, \ldots, N_{\text{tot}}\}$ where $N_{\text{tot}}$ stands for the total number of sites. Each site is initially a candidate for a
new wind farm. $N_t$ denote the number of sites that have been developed at time $t$. Once a site has been
developed, the corresponding wind farm operates until a predefined end of life. The decision to develop
a site is driven by economic incentives that are common to all sites and are synthesized by the reference
total return on investment $\mu_t$. This reference total return on investment has two components. The
first component is the intrinsic reference return of investment denoted by $\text{RoI}_t$ and which measures the
return on investment for a reference wind farm, in the absence of non technological learning from sites
already developed. Note that we do not constrain the reference return-on-investment to be the average
return over the whole population of sites. This point will be made more explicit when presenting
the calibration of the model. The actual return-on-investment benefits from learning about how to
deal with specific local conditions. Learning generates a second, contextual, component of the return
on investment that increases proportionally to the proportion $N_{t-1}/N_{tot}$ of sites already developed.
Consequently, $\mu_t$ may be written as

$$
\mu_t = \text{RoI}_t + \theta \frac{N_{t-1}}{N_{tot}}. 
$$

(1)

Nevertheless, the heterogeneity of sites, due to local conditions in terms of meteorological conditions
and in terms of accessibility for instance, implies that the return on investment fluctuates from one
site to another one. In order to capture the heterogeneity of sites without having to collect detailed
information site by site, we consider that the returns on investment $R$ over the whole population
follow a two parameters distribution with a partial density function $f(R; \mu_t, \sigma)$ where $\mu_t$ is a position
parameter and $\sigma$ is the standard deviation. The associated cumulative density function is denoted
$F(R; \mu_t, \sigma)$. Figure 1 shows such a distribution.

Figure 1: Micro-foundation dynamics and the RoI.
At a given time $t$, all sites with a positive return on investment $R$ are developed (or have been previously developed). Thus, the proportion $N_t/N_{\text{tot}}$ of sites developed at time $t$ is the surface $1 - F(0; \mu_t, \sigma)$ on the right of zero and below the curve representing the density function. If at time $t = 0$ the density function is null for all positive values of $R$, the diffusion of wind power cannot start. For diffusion to start, it is required that the intrinsic component $\text{RoI}_t$ of the return on investment increases. Such an increase may be due either to economic conditions that naturally improve (a higher price of electricity or a reduced generation cost resulting from innovation for instance) or to public support. At time $t$, the additional proportion $(N_t - N_{t-1})/N_{\text{tot}}$ of sites developed generates a learning effect that results in a higher average total return on investment at time $t + 1$. Ceteris paribus, the higher value of $\mu_{t+1}$ compared to $\mu_t$ induces a translation of the distribution of $R$ to the right. This effect can be either strengthened or weakened by a change in the intrinsic component of the total return so that the magnitude of the net translation is given by $\Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}}$ with $\Delta \text{RoI}_{t+1} = \text{RoI}_{t+1} - \text{RoI}_t$ and $\Delta N_t = N_t - N_{t-1}$. In case of a negative value of $\Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}}$, the diffusion process stops and will not restart until $\Delta \text{RoI}_{t+1}$ takes a positive value. The dynamics of the development of sites is formally described by the following equation.

$$\frac{\Delta N_{t+1}}{N_{\text{tot}}} = \left\{ \begin{array}{ll} F\left(\Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}}; \mu_t, \sigma\right) - F(0; \mu_t, \sigma) & \text{if } \Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}} > 0 \\ 0 & \text{if } \Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}} \leq 0 \end{array} \right.$$ (2)

This dynamics entails several properties of the diffusion process that make it appealing compared to the holistic approach.

2.1.3 Properties of the diffusion process

As already stressed, a first interesting feature of the dynamics of diffusion described by (2) is that, if the return on investment is initially negative for all sites, diffusion may need public support to start. Another interesting feature is that the diffusion can stop before full development, i.e. before $N_t = N_{\text{tot}}$. This arises when there is a combination of two elements: $\Delta \text{RoI}_{t+1}$ is negative and $\frac{\Delta N_t}{N_{\text{tot}}}$ was small. The first element results from a deterioration of economic conditions, the rise of the price of raw materials used to construct wind turbines or the lowering of public support for instance. The second element may arise from either previous bad economic conditions or, more importantly, from the shape of the distribution of the return on investment. Indeed, when many sites have already been developed, the remaining sites have their return on investment on the left tail of the distribution represented in Figure 1. 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 sites developed for a given translation $\Delta \text{RoI}_{t+1} + \theta \frac{\Delta N_t}{N_{\text{tot}}}$ of the distribution to the right. It follows on that the diffusion process is more likely to be stopped due to a decrease in $\text{RoI}_t$ when many sites have been already developed. This sharply contrast with the holistic approach that is not able to explain why the diffusion process can stop before being completed.

Another feature that substantially distinguishes the micro-founded model of diffusion from holistic models is that the dynamics of the proportion of sites developed is as much sensitive to the variations of economic incentives than to their absolute level. The absolute level of economic incentives is crucial
to determine the proportion of sites $1 - F(0; \mu_t, \sigma)$ developed at a given date $t$. As already mentioned above, the current level of economic incentives is captured by $\mu_t$ as defined in (2) which, in turn, is a key position parameter of the distribution of the return on investment. $\mu_t$ also appears in (2) but, even if it takes a high value, it can not generate the development of additional sites, unless $\Delta \text{RoI}_{t+1} + \theta \frac{\Delta N}{N_{\text{tot}}}$ is positive. This property is of importance to understand the results of the counterfactual analysis of the impact of public support. More specifically, if the benchmark scenario corresponds to a situation where public support has decreased over the period studied and this decrease is responsible for much of the global decrease of $\mu_t$, then it may be the case that suppressing the support once in all at the beginning of the period would have had a positive impact on the development of new sites compared to the benchmark.

Last but not least, there are two channels for learning in the micro-founded model proposed in the article. The first one is the direct effect of $\frac{N_{t-1}}{N_{\text{tot}}}$ on $\mu_t$. It captures non technological learning, such as a better knowledge of, and control on, the administrative process to be allowed to build a wind farm or a better understanding of local meteorological conditions. The second effect is indirect and works through the dynamics of the average intrinsic return on investment $\text{RoI}_t$. Indeed, $\text{ceteris paribus}$, $\text{RoI}_t$ increases due, for instance, to the decrease of the cost of equipments that results from the traditional learning curve. Mercure et al. [15], for instance, propose a micro-founded model close to the one presented in this article to explain substitution between technologies to produce electricity, but they focus on technological learning only. More specifically, they assume that investment decisions are based on the LCoE (a questionable assumption, as discussed latter on in this paper) and that the dynamics comes exclusively from the decrease of the cost of equipments that results from the cumulative production of these equipments. For now, we treat technological learning as exogenous but we will come back to this point latter on in this article.

2.2 Policy instruments and the profitability index.

2.2.1 Renewable energy development and the link with the RoI: a short literature review.

For the purpose of modeling, using a single criteria to trigger investment in new generation capacity is a meaningful alternative to the traditional optimization led decision process. As said above, Mercure et al. [15] develop a model of the electricity sector, driven by innovation, where investors make their decision relative to the Levelized Cost of Energy (LCoE) of the different generation technologies included in the model. In order to gain realism, the authors apply a probabilistic distribution to these LCoEs, representative of the geographical heterogeneity. However, using the LCoE to approximate the competitiveness of renewable energy power plants and the investment decisions has limits. As emphasized by Joskow [11], the LCoE is a flaw metric that does not take into account the generation time profile and the impact of its intermittency on the market revenue of producers. According to the same author, an alternative is to consider the expected profitability of power plants. In this vein, several studies have been realized using measures of the expected profitability of renewable power plants. We focus on the studies linking profitability and policy instruments supporting renewable energy. Mir-
Artigues and del Río [16] highlight the possibility to encompass several economic instruments by using the RoI. They review all the combinations of three types of instruments (revenue improving instruments, investment subsidies and low rate loans) that lead to the same level of RoI. Profitability metrics also make it possible to assess the changes in the design of an instrument. This is done in [6] and [9]. While the former does not build the bridge between the RoI of renewable energy power plants (more precisely, solar power plants in the paper) and the deployment of additional capacities, the latter does. In [9] the Net Present Value (NPV) of total production of a power plant is included in an econometric analysis. In our view, it is a first step to improve our understanding of the determinants of the investment in renewable energy power plants. Jenner et al. [10] estimate a fixed effects model based on the calculation of the RoI of two technologies: solar photovoltaic and onshore wind. By doing so, they estimate the effects of the revenue improving instruments in 26 countries. This study suggests several possible ways of improvement. First, it focuses on revenue improving instruments leaving aside the role of the cost alleviating instruments. Second, yearly LCoE are estimated with help of learning curves, hence assuming implicitly a steady decrease contrasting with the observed data [33].

2.2.2 How do policy instruments act on the RoI index?

The following formula is used to compute the RoI index of a cohort of producers\(^1\):

\[
RoI_{\text{Country}}^{\text{Cohort}} = \frac{\sum_{t=0}^{T} \left( P_t Q_t \right) - \left( IC_t MW + O&M_t Q_t \right) (1+a)^{-t} - DC_T (1+a)^{-T}}{\sum_{t=0}^{T} \left( IC_t MW + O&M_t Q_t \right) (1+a)^{-t} + DC_T (1+a)^{-T}}.
\]  

(3)

Where \( T \) is the power plant lifetime, \( P_t \) the price at which the electricity is sold at year \( t \), \( Q_t \) the generated output, \( IC_t \) the installed cost (spread in first years according to the loan conditions), \( MW \) the installed power, \( O&M_t \) the operation and maintenance costs and \( DC_T \) the decommissioning cost (also spread in the last years of the power plant). In the scope of this analysis, the main strength of the RoI index is to synthesize all market pull instruments aimed at trigger investment in renewable energy power plants. These instruments are summarized in the table 1 that presents the evolutions of policy support to onshore wind power in the six countries analyzed here during corresponding time periods. A more detailed version of this table is given in the Appendix A. United-Kingdom is not included in the analysis despite its installed wind power capacity. The reason is that the main support scheme in the United-Kingdom were the Renewable Obligations, a green certificates system. In order to be covered against the uncertainty of the certificates market, the majority of generators ask for bilateral contracts. The counterpart for risk hedging is that the electricity suppliers captured a significant share of the certificate’s price, according to [27]. Including the United-Kingdom in the sample substantially biases the analysis. In this article, a distinction is made between two types of market pull instruments. Instruments supporting the revenue part of the RoI index are called \textit{revenue improving} whereas instruments reducing the cost part of the RoI index are \textit{cost alleviating}. Within these two families there are several instruments. Revenue improving instruments included in the present analysis are:

\(^1\)In the remainder of this article, a cohort of producers will represent all the producers that enter the market the same year, thus reacting to the same economic context.
The Feed-in Tariff (FiT): it is the most frequently used demand support tool for promoting renewable energy. It makes it compulsory for system operator to buy each kWh of renewable electricity at a fixed rate, independently from market signals. The tariffs are defined for a given period and thus ensure the security of investments.

The Feed-in Premium (FiP): it is an alternative to the previous instrument. The principle is the same with the difference that producers receive a fixed premium on top of the market price. Hence the total payment varies with the price of electricity.

The Tradable Green Certificates (TGC): it provides a quantity-based instrument for renewable energy deployment. It requires electricity suppliers to supply a certain amount of renewable electricity. In order to demonstrate that they have complied with quotas electricity suppliers must present the corresponding quantity of certificates. Then a green certificates market is established, its price being the support to renewable electricity producers (in addition to the market revenue).

Cost alleviating instruments included in the RoI index are:

- *Investment subsidy*: it reduces the investment cost. It may cover all or parts of the investment costs (i.e. the turbine, the civil work, etc.).

- *Helped loan*: it guarantees preferential funding conditions for renewable energy producers. In most of the cases it relates to loan rate below the market rates. In some cases, low rates are coupled with different reimbursement period lengths or possibilities to extend the repayment period.

- *Reduced VAT rate*: reduced VAT rates for renewable equipment. According to [23], ‘reduced VAT rates can be similar as investment subsidies’. However, it affects only the turbine price and not the all investment cost.

RoI index is an average margin rate for each kWh sold by the producer. It makes sense to consider it as a crucial determinant of the investment. However, it suffers from several weaknesses. First, it does not take into account the uncertainty affecting investments in renewable energy sectors (two sources of uncertainty must be mentioned: the meteorological uncertainty affecting the plant’s productivity and the regulatory one caused by changing policy regimes). Second, it does not fairly reflect the grid connection constraint, even if the cost of this connection is included in investment costs it exists a wide heterogeneity of this cost among installations.

### 2.2.3 Assumptions and data.

A complete description of assumptions and data used for computing the RoI index is given in Appendix B. Here, emphasize is on the sources of heterogeneity captured by the index through available data.

The first source of heterogeneity is technological. Despite the fact that the wind turbine market is more and more international, several national factors play on the cost of this technology. This
Table 1: Instruments of support to onshore wind in six European countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
<th>Phase 5</th>
<th>Phase 6</th>
</tr>
</thead>
</table>

technological heterogeneity is partly caught by the data on IC which mainly comes from the IEA Wind national reports [32]. It allows for a country specific estimation of wind energy costs and faithfully transcribes their evolutions time profiles.

The second source of heterogeneity is geographic, which is of special importance for intermittent energies such as wind power. It can be approximated by using national load factors. Load factors are the ratio between the produced output per year and the maximum theoretical production (measured by the installed capacity). Based on Boccard [4] the productivity of a typical wind site is computed for each country. The main weakness of this strategy is to retain one value per country for every years of the time sample. This issue is addressed in the Danish case for which it is possible to estimate a load factor for each cohort in order to capture the technical progress in turbines efficiency from a year to another. Due to a lack of data, it is not possible for other countries.

The last source of heterogeneity is economic. The economic background defines several parameters such as loan rates, average risk-free financial returns in the Euro zone (used in this paper as discounting rates) and electricity prices. The latter fulfills three roles in this analysis:

- In the case of a FiP, a part of producers revenue comes from the electricity market.
• When the revenue improving scheme ends, producers only receive the market price.
• In order to build the counter-factual analysis, a set of indicators without any revenue improving support must be calculated.

It must be underlined that the counter-factual analyze investigates the case for no financial support but cannot dispose from the priority access to the grid assumption. More, it is difficult to apprehend the time profile of the wind production that defines producers revenue. Most of the time, windier hours occur during off-peak hours, preventing wind producers from recovering their fixed costs [3]. In this analysis only yearly average prices are retained in the RoI index.

2.2.4 Dynamics of the RoI.

![Figure 2: Evolution of the RoI for the six European countries.](image)

The temporal dynamics of the national RoI over the covered time sample is presented in the figure 2. Several characteristics of the RoI can be emphasized. First, high levels of profitability are reached. More, the countries with the higher levels are not necessarily those with the bigger wind power installed capacity, as in the Italian case for instance. This high level of profitability has been already underlined in the literature (see for instance [10]). Second, the RoI is characterized by a strong volatility over time. These volatility is conditional to several factors. First, market pull policies have experienced substantial changes. In most of the cases, these changes occurred in revenue improving support resulting from the modification of the length of the scheme, the level of payment or the chosen economic instrument. The second source of volatility is the evolution of the investment costs over time. These costs followed an intuitive decrease due to learning in the first years of the 2000s. But the raw materials prices and the demand for wind turbine raised, resulting in a strong stress on the market, and investment cost
started to increase around the year 2006. Since wind power investments are highly capitalistic, the RoI is also highly sensitive to the investment cost variations. Finally, the macroeconomic crisis is faithfully transcribed through loans rates, discount rates and electricity prices (for FiP and TGC cases) as shows the collapse of RoIs in 2008.

2.3 Model calibration.

2.3.1 Open loop calibration

The purpose of the quantification of the parameters involved in the dynamic equation (2) is to conduct a counterfactual analysis of the impact of different policy instruments on the development of new onshore capacities for wind power. 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 sites starting from the same initial conditions than those that have actually prevailed, but proceeding with fictitious values of the intrinsic return on investment. For this purpose, we have to make sure that, at least, the values used for the parameters enable us to correctly reproduce the time path observed with the actual values of RoI$^t$. The open loop approach requires to compute the predicted proportion of sites developed at dates $t > 0$ on the basis of the initial proportion at date $t = 0$. If the dynamic equation (2) was linear, it could be done analytically and we would be able to estimate the parameters with standard econometric methods. The point is that (2) is highly non linear and that we are not able to find a simple and econometrically tractable analytical expression of $N^t / N^{tot}$ as a function of $N^t / N^{tot}$. 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.

In order to calibrate the model, 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 $N^t / N^{tot}$ over the whole period of the study, conditionally on its initial value $N^0 / N^{tot}$ and conditionally on the observed values of RoI$^t$. The set of parameters’ values that minimizes the root mean square error between the simulated proportions $N^t / N^{tot}$ and their actual values is used as the solution. A new minimization, based on a narrower grid with smaller increment between the values of parameters, is implemented until the root mean square error obtained for the solution does not decrease more than an fixed relative value. Parameters subject to this minimization are the coefficient $\theta$ of learning, the dispersion parameter $\sigma$ of the distribution of the return on investment and the maximum number $N^{tot}$ of sites that can be used to install a wind farm. Note that, contrary to most technology diffusion problems, we do not know $N^{tot}$ but have to calibrate it like other parameters.

Last but not least, prior calibrating the parameters we need to specify a distribution function $f$ for the return on investment. For limiting the number of parameters while allowing enough flexibility, we restrain the analysis to distributions with two parameters, a position parameter tightly linked to $\mu_t$ and a dispersion parameter $\sigma$. A natural candidate is the Gaussian distribution with expected value $\mu_t$ and standard deviation $\sigma$. Nevertheless, like all symmetric distributions, it has an important disadvantage: if the initial value of the average total return on investment is positive (i.e. $\mu_t > 0$), then at least half
of the sites should be developed at the initial date \( t = 0 \). This is obviously too restrictive. Therefore, we rather use a truncated (on the right) version of the Gaussian distribution:

\[
f(R; \mu_t, \sigma) = \begin{cases} 
\frac{\varphi(R; \mu_t, \sigma)}{\Phi(R_{\text{max}}; \mu_t, \sigma)} & \text{if } R \leq R_{\text{max}} \\
0 & \text{if } R > R_{\text{max}} 
\end{cases}, \quad \text{with } R_{\text{max}} > 0
\]

(4)

where \( \varphi(R; \mu_t, \sigma) \) and \( \Phi(R; \mu_t, \sigma) \) are respectively the partial density function and the cumulative density function of the Gaussian distribution with expected value \( \mu_t \) and standard deviation \( \sigma \). For given values of \( \theta, \sigma \) and \( N_{\text{tot}} \), the upper bound \( R_{\text{max}} \) is calibrated so that the initial proportion of developed sites just coincides with the observed proportion \( N_0/N_{\text{tot}} \) at time \( t = 0 \). This initial condition is formally written as

\[
1 - F(0; \mu_0, \sigma) = \frac{N_0}{N_{\text{tot}}}
\]

(5)

or equivalently

\[
\frac{\Phi(R_{\text{max}}; \mu_0, \sigma) - \Phi(0; \mu_0, \sigma)}{\Phi(R_{\text{max}}; \mu_0, \sigma)} = \frac{N_0}{N_{\text{tot}}}
\]

(6)

Due to the truncation, \( \mu_t \) remains the mode of the distribution but is no longer the expected return. Instead, the expected return on investment over the whole population of sites is, according to [24],

\[
E[R] = \mu_t - \sigma \frac{\varphi(R_{\text{max}}; \mu_0, \sigma)}{\Phi(R_{\text{max}}; \mu_0, \sigma)}
\]

(7)

An alternative specification for the distribution of the return on investment 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. Like for the Gaussian distribution, if \( \mu_t \) is the position parameter then the proportion of sites developed at time \( t = 0 \) generally exceeds \( N_0/N_{\text{tot}} \). To remedy to this problem and satisfy (5), the distribution is also truncated on the right.

2.3.2 Values set for the parameters

Although previous studies that analyze the development of wind power have used data on installed capacities, it would not be consistent with our micro-founded model of diffusion. Indeed, what is explained by the micro-founded model is whether the investor finds it optimal to develop a site, not which capacity will be installed. The link between the installed capacity and the development of a site will be examined latter on this paper and is mostly based on technological progress. With this remark in mind, we chose to use the database The Wind Power which collects information about wind power sites all around the world\(^2\). A comparison between the cumulative installed capacities computed from this database for each of the six countries we study and the cumulative capacities reported on the

\(^{2}\)For more information on the database see at http://www.thewindpower.net/index.php

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Table 2: Estimation results by country

<table>
<thead>
<tr>
<th>Distribution function of the RoI</th>
<th>DK</th>
<th>DE</th>
<th>FR</th>
<th>IT</th>
<th>SP</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$N_{tot}$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaussian $\theta$</td>
<td>2.9429</td>
<td>29.75</td>
<td>63.5</td>
<td>220.0</td>
<td>59.45</td>
<td>59.075</td>
</tr>
<tr>
<td>Gaussian $\sigma$</td>
<td>2.30286</td>
<td>24.0714</td>
<td>19.10</td>
<td>91.7151</td>
<td>19.01</td>
<td>12.3443</td>
</tr>
<tr>
<td>RMSE</td>
<td>56.3908</td>
<td>31257.7</td>
<td>193.7151</td>
<td>6.03882</td>
<td>20.681</td>
<td></td>
</tr>
<tr>
<td>Relative RMSE</td>
<td>0.23385</td>
<td>0.0645403</td>
<td>0.094203</td>
<td>0.0334354</td>
<td>0.0397533</td>
<td></td>
</tr>
<tr>
<td>RMSE/mean($N_t$)</td>
<td>0.0785586</td>
<td>12.2531</td>
<td>0.382963</td>
<td>2.88166</td>
<td>0.073852</td>
<td>0.166369</td>
</tr>
<tr>
<td><strong>$\kappa$</strong></td>
<td>2022.4</td>
<td>11113.4</td>
<td>1166.07</td>
<td>515.657</td>
<td>247.858</td>
<td>474.129</td>
</tr>
<tr>
<td>Extreme Values $\theta$</td>
<td>3.03929</td>
<td>9.16857</td>
<td>29.5014</td>
<td>225.0</td>
<td>26.4986</td>
<td>16.5679</td>
</tr>
<tr>
<td>Extreme Values $\sigma$</td>
<td>1.352</td>
<td>8.74286</td>
<td>10.6714</td>
<td>110.0</td>
<td>110.0</td>
<td>7.05651</td>
</tr>
<tr>
<td>RMSE</td>
<td>3544.95</td>
<td>30029.4</td>
<td>36.7363</td>
<td>150.064</td>
<td>5.90143</td>
<td>24.4137</td>
</tr>
<tr>
<td>Relative RMSE</td>
<td>0.232967</td>
<td>0.0632444</td>
<td>0.0715909</td>
<td>0.171414</td>
<td>0.0403525</td>
<td>0.0486726</td>
</tr>
<tr>
<td>RMSE/mean($N_t$)</td>
<td>4.94021</td>
<td>11.7716</td>
<td>0.138715</td>
<td>1.45259</td>
<td>0.0721718</td>
<td>0.196397</td>
</tr>
</tbody>
</table>

website of *European Wind Energy Association*\(^3\) shows that the census of sites in the database is almost exhaustive. The date of commissioning is not always reported and the proportion of sites for which this information is available greatly differs from one country to another one (98.85% for Denmark, 87.85% for Germany, 93.46% for France, 58.30% for Italy, 15.21% for Spain and 99.58% for Portugal). We assume that this proportion is stable but there is clearly a risk that results are less reliable for countries with a low proportion, more specifically Italy and Spain.

Parameters of the model are calibrated country by country. The theoretical time path of the count of developed sites is computed from the dynamic equation (2) multiplied by the parameter $N_{tot}$ which is itself calibrated. By contrast with most empirical studies on technology diffusion, we do not have information on the total number of potential adopters. Nevertheless, $N_{tot}$ can be calibrated like other parameters. Detailed results on calibration are provided by Table 2. The value of the parameters varies greatly from one country to another one, but also from one distribution to another one. The Gaussian distribution yields the minimum RMSE for Denmark and Portugal. The minimum RMSE is obtained with the extreme value distribution for the four other countries. Although the RMSE is the minimization criteria, the relative RMSE and the ratio of the RMSE to the mean value of the number of developed sites over the period are also displayed in Table 2. The relative RMSE measures the mean ratio between the quadratic error observed and the cumulative number of developed sites at each date. The relative RMSE and the ratio between the RMSE and mean value of $N_t$ are intended to ease the comparison between countries. Nevertheless, neither of them is perfect. The relative RMSE put a similar weight on each date, whatever the number of sites developed. Yet, a ten percent error on a small number of developed sites is probably less worrying than a ten percent on a large number of developed sites. For its part, the ratio between the RMSE and the mean number of developed sites is sensitive to the general shape of the diffusion. Therefore, in order to complete Table 2, Figures 3 and 4 provide a visual comparison of the rate of diffusion computed from the observed count of developed sites and the rate of diffusion computed from the simulated count. The diffusion has been simulated only for the period where data required to compute the *RoI* were available. For all countries, this period ends in 2012 whereas data on newly commissioned wind farms were available until 2014. The period

\(^3\)http://www.ewea.org/
studied starts in 1985 for Denmark, which is the longest period. As a result, the calibration enables to simulate a time path of the diffusion which is particularly close to the observed one. The period starts in 2000 for the other countries (except for France for which it starts in 2001). The observed and the simulated time paths of diffusion are also close to each other for France, Portugal and, to a less extent, for Germany (except at the end of the period). Calibration results in some gaps between the two time paths for Italy and Spain which are also the two countries where the rate of missing dates of commissioning was high and the population of studied wind farms is likely to be less representative of the whole population of developed sites.

Figure 3: Realized versus estimated deployed capacities (gaussian distribution)
Figure 4: Realized versus estimated deployed capacities (extreme values distribution)

Another contribution of Figures 3 and 4 is that they highlight how large is the remaining potential of development. This potential should be interpreted with caution because it relies on the calibrated value of $N_{tot}$ and reflects the social acceptability of wind farms, as much as the physical availability of interesting sites. This explains for instance why France, where the physical potential is likely to be greater than in Germany and where the number of sites developed is much lower, is considered as having reached more than 60% of its potential whereas Germany is still under 40% of its potential. Table 3 complements the description of the calibration. It gives information on the main characteristics of the distribution of the intrinsic $RoI$. These characteristics derives from the values of parameters
displayed in Table 2 and, unsurprisingly, they also greatly vary from one country to another one. Denmark and Italy appears to be the countries with respectively the lowest and the highest dispersion of the intrinsic RoI.

<table>
<thead>
<tr>
<th>Distribution function of the RoI</th>
<th>DK</th>
<th>DE</th>
<th>FR</th>
<th>IT</th>
<th>SP</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t=T$</td>
<td>2012</td>
<td>2012</td>
<td>2012</td>
<td>2012</td>
<td>2012</td>
<td>2012</td>
</tr>
<tr>
<td>$R_{max}$ at $t=0$</td>
<td>0.00198937</td>
<td>0.864472</td>
<td>0.318057</td>
<td>2.52105</td>
<td>1.05322</td>
<td>0.395275</td>
</tr>
<tr>
<td>Mean at $t=T$</td>
<td>1.90174</td>
<td>-16.5917</td>
<td>10.8276</td>
<td>-48.2872</td>
<td>11.4912</td>
<td>2.71064</td>
</tr>
<tr>
<td>Median at $t=0$</td>
<td>-1.52983</td>
<td>-15.3979</td>
<td>-12.3121</td>
<td>-58.3841</td>
<td>-11.0437</td>
<td>-7.81265</td>
</tr>
<tr>
<td>Standard Deviation at $t=0$</td>
<td>1.37771</td>
<td>14.5233</td>
<td>11.3899</td>
<td>54.8194</td>
<td>11.0981</td>
<td>7.3835</td>
</tr>
<tr>
<td>Variation coefficient at $t=0$</td>
<td>-0.75929</td>
<td>-0.790706</td>
<td>-0.77617</td>
<td>-0.786249</td>
<td>-0.828068</td>
<td>-0.79065</td>
</tr>
<tr>
<td>$R_{max}$ at $t=T$</td>
<td>0.724446</td>
<td>-0.875339</td>
<td>1.05194</td>
<td>-1.13528</td>
<td>0.965792</td>
<td>2.72389</td>
</tr>
<tr>
<td>Mean at $t=0$</td>
<td>-0.877959</td>
<td>-4.81241</td>
<td>-6.6251</td>
<td>-1.47547</td>
<td>-5.85131</td>
<td>-4.72623</td>
</tr>
<tr>
<td>Mean at $t=T$</td>
<td>1.53119</td>
<td>-2.8179</td>
<td>9.46394</td>
<td>21.1629</td>
<td>8.23526</td>
<td>2.73457</td>
</tr>
<tr>
<td>Median at $t=0$</td>
<td>-0.815137</td>
<td>-4.43321</td>
<td>-6.15253</td>
<td>-61.8942</td>
<td>-5.3228</td>
<td>-4.38302</td>
</tr>
<tr>
<td>Median at $t=T$</td>
<td>1.59401</td>
<td>-2.43669</td>
<td>9.96022</td>
<td>11.0622</td>
<td>8.76377</td>
<td>3.07779</td>
</tr>
<tr>
<td>Standard Deviation at $t=T$</td>
<td>0.564309</td>
<td>3.81772</td>
<td>4.45032</td>
<td>80.1459</td>
<td>4.39033</td>
<td>3.2409</td>
</tr>
<tr>
<td>Variation coefficient at $t=T$</td>
<td>-0.64275</td>
<td>-0.793077</td>
<td>-0.671737</td>
<td>-54.319</td>
<td>-0.790316</td>
<td>-0.685726</td>
</tr>
</tbody>
</table>

Table 3: Characteristics of the distribution of the RoI

3 Results.

This section gives a first overview of the evolution of the actual return-on-investment (RoI) if the six European countries. Simple graphics underline the imbalance between revenue improving and cost alleviating instruments. The two last subsections go further in the analysis by presenting the simulation results of two counterfactual scenarios: each isolating the role of the two instruments families.

3.1 Counter-factual analysis of the profitability index.

First elements of the counter-factual analysis are given here. They are represented on two graphics. The figure 5 presents the difference between a ROI including all the support instruments and a ROI that only contains the support instruments of the type cost alleviating. Thus, the bigger is the difference the more revenue improving instruments are important in the wind farm profitability. The second figure 6 presents the alternative analysis, excluding the effect of cost alleviating instruments. These two graphics emphasize several results. First, it underlines the prominence given to revenue improving instruments. It shows that the strong volatility of the RoI directly results from the support to revenue. In fact, the profitability is relatively stable over the time when considering only the role of
cost alleviating instruments. At the contrary the part of the RoI imputable to the revenue improving instruments is high and volatile. This is consistent with [10].

Figure 5: ROI difference between full support and support without revenue improving instruments.

Second, it is obvious that the choice of the revenue improving instrument does not predetermine the evolution of the profitability. It is demonstrated by the cases of the Denmark and the Spain, who both chose to implement a premium during a long period (see Table 1), and show highly contrasted RoI dynamics.

Third, it is clear that using cost alleviating instruments is a good strategy since it induces more stable profitability level. This is due to the role of investment cost in the profitability of highly capitalistic investment as wind farms are. Again, Denmark reveals a interesting strategy by generously supporting the investment in wind farm at the beginning of the time period and progressively reducing this support. In fact, this early support has shaped the installed capacity time path on the all period.

3.2 Impact of revenue improving instruments on installed capacities.

Figure 5 illustrates the counterfactual analysis of the impact of revenue improving policy instruments. It is completed by Table 4 which provides some statistics on this impact. The counterfactual analysis consists in simulating what would have been the development of wind farms if the revenue improving policy instruments had not exist. For this purpose, the actual values of the intrinsic RoI are replaced by their counterfactual values presented just above and the dynamic model described by equation 2 is run starting at the observed cumulative count of developped sites at the first date of the period studied. The counterfactual analysis thus combines a direct effect and an indirect effect of policy instruments. The direct effect follows on from the change on values of the intrinsic RoI. The indirect effect is induced by the learning effect incorporated in the total RoI. Indeed, the impact of a change in the
Figure 6: ROI difference between full support and support without cost alleviating instruments.

<table>
<thead>
<tr>
<th>Distribution function of the ROI</th>
<th>DK</th>
<th>DE</th>
<th>FR</th>
<th>IT</th>
<th>SP</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-16.42</td>
<td>-10.37</td>
<td>-4.61</td>
<td>-7.02</td>
<td>0.12</td>
<td>-24.29</td>
</tr>
<tr>
<td>Median</td>
<td>0.32</td>
<td>-9.98</td>
<td>-5.18</td>
<td>-7.18</td>
<td>1.05</td>
<td>-25.32</td>
</tr>
<tr>
<td>Minimum</td>
<td>-80.54</td>
<td>-14.47</td>
<td>-7.99</td>
<td>-7.93</td>
<td>-0.09</td>
<td>-31.95</td>
</tr>
<tr>
<td>Maximum</td>
<td>24.63</td>
<td>3.39</td>
<td>0.57</td>
<td>-4.98</td>
<td>2.94</td>
<td>-13.81</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>41.54</td>
<td>3.27</td>
<td>2.81</td>
<td>0.86</td>
<td>1.08</td>
<td>-6.25</td>
</tr>
</tbody>
</table>

| Mean                            | -32.28    | -10.95    | -13.70    | -5.42     | -1.81     | -38.34    |
| Median                          | -40.79    | -10.76    | -13.66    | -5.92     | -1.68     | -39.82    |
| Maximum                         | 12.02     | -3.65     | -5.60     | -3.08     | -0.59     | -26.06    |
| Standard Deviation              | 36.04     | 3.35      | 5.32      | 1.02      | 0.98      | 4.64      |

Table 4: Counterfactual impact of suppressing revenue improving support (statistic on the simulated capacity measured as a % of actual capacity)

intrinsic $RoI$ implies that the number of new wind farms commissioned at each date differs from the actual number which, in turn, affects the degree of learning for all future dates. Moreover, as already stressed when discussing Figure 2, the dynamics of the micro-founded model of technology diffusion depends not only on the level of the total return on investment, but also on its variations. Therefore, it is not that obvious to anticipate how the results of the counterfactual analysis for the intrinsic $RoI$ translate in terms of simulated diffusion of wind power.

A striking feature of Figure 7 and Table 4 is that the suppression of revenue improving policy instruments would punctually have had a positive impact on the diffusion of wind power. This is more specifically the case of Denmark from 2000 to 2012 and for Spain. The case of Denmark is illustrative of the importance of variations of the intrinsic $RoI$. Globally speaking, without revenue...
Figure 7: Impact of revenue improving policy instruments (in % of the developed sites)

improving instruments, the mean impact of suppressing these instruments would have been negative. Denmark is even one of the two countries, with Portugal, that exhibits the stronger negative mean impact. By contrast, the diffusion of wind power in Spain would have been almost not affected by a suppression of revenue improving instruments. It may be interpreted as the predominance of the role of natural favorable conditions (the load factor for wind turbine in Spain is among the highest in Europe) compared to economic incentives. The counterfactual analysis also reveals a mitigated impact of revenue improving instruments in Italy whereas this impact is significant, although smaller than for Denmark and Portugal, in France and in Germany. Note however that Italy and Spain are the
two countries for which the study does not include all wind farms because the rate of missing dates of commissioning is high. All in one, it turns out that revenue improving policy instruments have had a significant and positive role in the diffusion of wind power in countries where we have an almost exhaustive information on the dates of commissioning of wind farms.

### 3.3 Impact of cost alleviating instruments on installed capacities.

<table>
<thead>
<tr>
<th>Distribution function of the RoI</th>
<th>DK</th>
<th>DE</th>
<th>FR</th>
<th>IT</th>
<th>SP</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>73.38</td>
<td>-1.14</td>
<td>0</td>
<td>-0.52</td>
<td>0</td>
<td>-0.36</td>
</tr>
<tr>
<td>Median</td>
<td>19.78</td>
<td>-1.23</td>
<td>0</td>
<td>-0.52</td>
<td>0</td>
<td>-0.39</td>
</tr>
<tr>
<td>Gaussian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>10.16</td>
<td>-1.48</td>
<td>0</td>
<td>-0.65</td>
<td>0</td>
<td>-0.81</td>
</tr>
<tr>
<td>Maximum</td>
<td>446.57</td>
<td>-0.33</td>
<td>0</td>
<td>-0.32</td>
<td>0</td>
<td>0.13</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>99.19</td>
<td>0.34</td>
<td>0</td>
<td>0.10</td>
<td>0</td>
<td>0.30</td>
</tr>
<tr>
<td>Mean</td>
<td>36.38</td>
<td>-1.18</td>
<td>0</td>
<td>-0.46</td>
<td>0</td>
<td>-1.55</td>
</tr>
<tr>
<td>Median</td>
<td>5.98</td>
<td>-1.28</td>
<td>0</td>
<td>-0.51</td>
<td>0</td>
<td>-1.61</td>
</tr>
<tr>
<td>Extreme Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>1.97</td>
<td>-1.54</td>
<td>0</td>
<td>-0.54</td>
<td>0</td>
<td>-2.24</td>
</tr>
<tr>
<td>Maximum</td>
<td>505.38</td>
<td>-0.34</td>
<td>0</td>
<td>-0.21</td>
<td>0</td>
<td>-0.57</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>94.30</td>
<td>0.36</td>
<td>0</td>
<td>0.11</td>
<td>0</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 5: Counterfactual impact of suppressing cost alleviating support (statistic on the simulated capacity measured as a % of actual capacity)

Figure 8 and Table 5 are parallel to Figure 7 and Table 4 but they highlight the counterfactual analysis of the impact of cost alleviating policy instruments on the development of wind farms. It appears from the outset that the impact of cost alleviating policy instruments is much lower than that of revenue improving policy instruments. This is in line with what we already observed in the counterfactual analysis of the intrinsic value of the RoI. A noticeable and troubling exception is Denmark. Once again, the suppression of policy instruments in this country would have had a positive impact on the diffusion of wind power. Nevertheless, this impact is largely due to the fact that cost alleviating instruments have been substantially weakened from the start of the eighties to the end of the nineties. The slowdown of support has implied a decrease of the intrinsic RoI over all that period *ceteris paribus*. In the absence of any cost alleviating instrument, this slowdown would have not occurred and, therefore, the impact on the dynamics of diffusion would have been positive. Denmark aside, the suppression of cost alleviating policy instruments would have had a negative impact, though quite limited. The most impacted are Germany and, to a lesser extent, Portugal and Italy (depending on the distribution of RoI considered).

### 4 Conclusion.

Whether public support to the development of wind power has had a significant impact on this development crucially depends on the type of instrument considered and on the country. The counterfactual analysis of the impact of the different instruments used in several European countries clearly shows
that the higher impact comes from instruments that intend to improve revenues of wind farms whereas instruments that aim at alleviating cost of investing in, and operating, wind farms had a rather limited impact. Nevertheless, this mainly reflects the fact that public policies have favored the first type of instruments. The dependence on the country studied is likely to result from the sensitivity of technology diffusion to variations in economic incentives. Indeed, a peculiar property of the micro-founded diffusion model proposed in this article and implemented for the counterfactual analysis is that variations of intrinsic profitability around a trend do not generate the same diffusion that the trend itself. Some countries may have been keen in sending stable signals to investors whereas others have been

Figure 8: Impact of cost alleviating policy instruments (in % of the developed sites)
subject to repeated regulatory changes. Said another way, a sudden and sharp drop of the support can annihilate previous efforts to develop wind power and stop its diffusion process. This result does not mean that public support should never been suppressed but that public authorities should be more cautious about how to suppress it.

A Appendix A: Historical evolution of the support schemes in the six European countries.

A detailed version of table 1 is given in the tables 6 and 7.

<table>
<thead>
<tr>
<th></th>
<th>Revenue Improving Instruments</th>
<th>Cost Alleviating Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FiT</strong></td>
<td><strong>FiP</strong></td>
<td><strong>TGC</strong></td>
</tr>
<tr>
<td><strong>Phase 1</strong></td>
<td><strong>Phase 4</strong></td>
<td><strong>Helped Loans</strong></td>
</tr>
<tr>
<td>Denmark (1985-2012)</td>
<td>85% of the Local Retail Price (LRP), taxes excluded</td>
<td>25% of the IC (1985)</td>
</tr>
<tr>
<td>Phase 2</td>
<td>Premium of 13 4MWh (lifetime, total payment capped to 48 4MWh)</td>
<td>15% of the IC (1986-1988)</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Premium of 36 4MWh for the first 22 000 full load hours, then 3 4MWh (lifetime)</td>
<td>10% of the IC (1989)</td>
</tr>
</tbody>
</table>

France (2001-2012)

<table>
<thead>
<tr>
<th><strong>Phase 1</strong></th>
<th><strong>Phase 2</strong></th>
<th><strong>Phase 3</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>83.8 4MWh for the 5 first years, then from 30.5 to 83.8 4MWh for 10 years (depending on the site productivity)</td>
<td>82 4MWh for the 10 first years, then from 28 to 82 4MWh for 10 years (depending on the site productivity)</td>
<td>50 4MWh for 8 years, then 69 4MWh (lifetime)</td>
</tr>
</tbody>
</table>

Italy (2000-2012)

<table>
<thead>
<tr>
<th><strong>Phase 1</strong></th>
<th><strong>Phase 2</strong></th>
<th><strong>Phase 3</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>180 4MWh for 8 years, then 50 4MWh (lifetime)</td>
<td>Market revenue plus the green certificates price (for 8 years)</td>
<td>Support period increases from 8 to 12 years</td>
</tr>
</tbody>
</table>

Table 6: Instruments of support to onshore wind (first part)

4 Instruments included in the RoI index are written in italics.
5 The sources for the Denmark are [32], [19], [17], [33] and http://www.ens.dk/sites/ens.dk/files/supply/electricity/conditions-production-plants/subsidies-generation-electricity/The%20history%20of%20Danish%20support%20for%20wind%20power.docx.
6 From [33] and [17].
7 From [35].
<table>
<thead>
<tr>
<th>Phase</th>
<th>Revenue Improving Instruments</th>
<th>Phase</th>
<th>Cost Alleviating Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2 (2004-2006)</td>
<td>90% of the Average Electricity Tariff (AET) for 15 years</td>
<td>Phase 2 (2004-2006)</td>
<td>A premium equals to 40% of the AET, plus 10% if the production is sold on the market</td>
</tr>
<tr>
<td>Phase 3 (2007-2012)</td>
<td>Tariffs are indexed on the retail price and are guaranteed for 20 years. In 2008 the payment was 75.6 €/MWh</td>
<td>Phase 2 (2007-2012)</td>
<td>A cap on the total payment is introduced. In 2011 the premium is reduced by 35%</td>
</tr>
<tr>
<td>Phase 1 (1999-2001)</td>
<td>60 €/MWh for the first 12 years</td>
<td>(2001-2006)</td>
<td>Zero rate loans up to 25,000 € of total IC</td>
</tr>
<tr>
<td>Phase 2 (2002-2004)</td>
<td>82 €/MWh for 20 years</td>
<td>(2001-2004)</td>
<td>5% instead of 17%</td>
</tr>
<tr>
<td>Phase 3 (2005-2012)</td>
<td>76 €/MWh for 15 years, reduced to 74 €/MWh after 2007</td>
<td>(2005-2007)</td>
<td>21%</td>
</tr>
<tr>
<td>Phase 2 (2006-2008)</td>
<td>91 €/MWh for 5 years</td>
<td>(2008-2009)</td>
<td>20%</td>
</tr>
<tr>
<td>Phase 2 (2009-2012)</td>
<td>The payment is 92 €/MWh with an annual decrease of 1%</td>
<td>(2010)</td>
<td>20% and 23%</td>
</tr>
</tbody>
</table>

Table 7: Instruments of support to onshore wind (second part)

8Royal 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 [22], only the premium option is considered for the RoI index computing.

9According to the Royal Decree 2818/1998, the FiT is guaranteed for five years. However, it contains a provision guaranteeing unlimited availability of premiums and therefore, indirectly, automatic renewal of purchase contracts [22]. A survey conducted among 40 renewable energy producers demonstrated the minor role of the uncertainty on purchase contracts renewal [22].

10The 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 [32].

11To compute the RoI index, the premium option is retained since ‘90% of wind producers have opted for the FiP-support’ according to [18].

12Cap and floor prices are indexed on the electricity retail price. In 2008, the values were 73.6 €/MWh and 87.8 €/MWh.

13According to the Royal Decree 1614/2010.
Appendix B: Assumptions and data

This appendix provides for further information about the assumptions made and the data used in this article. It constitutes a detailed version of the subsection 2.2.3.

B.1 Technological assumptions and data

B.1.1 Typical installation and lifetime

The chosen typical installation is a onshore wind turbine with an installed power of 1 MW. Obviously it is impossible to choose an installed capacity that truly reflects the wind power park in the six European countries. However, the RoI index is almost insensitive to the size of installation since it only impacts the decommissioning cost. In fact the challenge was to choose a size which is representative of the most supported technological subset of onshore wind plants in terms of revenue improving policies\textsuperscript{17}. The retained assumption for the power plant lifetime is 20 years.

B.1.2 Investment Costs (IC)

According to the IPCC \cite{36}, IC for an onshore wind plant encompass turbine cost, grid connection costs, civil work costs and other costs (transaction costs, land cost, etc.). The main sources are the IEA Wind national reports that provide for annual data on IC for several countries: Denmark (1985-2012), Italy (2000-2012), Spain (2000-2012), Germany (2003-2012) and Portugal (2003-2012). For the French case data are few, the first source is a study made by the french regulatory commission (Commission de Régulation de l’Énergie) \cite{28} and provides for the years 2007 to 2012. The second is a study from the french agency of environment (ADEME) and provides for the IC of the year 2001 \cite{26}. A linear interpolation is made to estimate missing values. Since this period corresponds to a general decrease tendency in the other countries, it is unlikely to hamper our results. For the Portugal, IEA Wind reports underline the fact that the values for 2003, 2004, 2005, 2009 and 2010 do not include grid connection cost and civil work, in order to address this issue we increase IC values by 17\% based on the IPCC report \cite{36}. Finally the missing values for the first years in Portugal and Germany are estimated by replicating the Danish IC trend. This trend is obtained from the data in \cite{25}.

B.1.3 Operation and Maintenance Costs (O&M)

O&M costs are composed by insurance cost, production management and its prevision, 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 values for the six countries. Data is from the 2010 Wind Technologies Market Report \cite{37}.

\textsuperscript{14} According to \cite{30}.
\textsuperscript{15} According to \cite{30}.
\textsuperscript{16} From \cite{34}, \cite{29}, \cite{17} and \cite{13}.
\textsuperscript{17} Typically, when a FIT is implementing there is a distinction between several subsets of installations depending on the installed power. For example, the tariff will be higher for small power plants and lower for big power plants.
B.1.4 Decommissioning Cost (DC)

Several ways to apprehend DC can be found in the literature. The retained assumption is that DC cost equals to 5% of the IC as in the IEA report on electricity cost [31], DC is paid by producer at the last year of operation of the power plant.

B.2 Geographical assumptions and data

B.2.1 National load factors

The load factor of a power plant measures the ratio between the yearly quantity of generated output and the maximum load in a year. Then, for an onshore wind turbine it depends from meteorologic conditions. Assumptions about the load factor of a wind turbine may vary significantly from a study to another. In this article, the retained values are from Boccard [4] that computes the realized values of the wind power load factors for several European countries. They are given in the table 8. The study of Boccard only focuses on years 2003-2007, the resulting values are assumed to be representative of all the time sample.

<table>
<thead>
<tr>
<th>Country</th>
<th>France</th>
<th>Spain</th>
<th>Italy</th>
<th>Germany</th>
<th>Portugal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average realized load factors between 2003 and 2007</td>
<td>22.3%</td>
<td>24.8%</td>
<td>19.1%</td>
<td>18.3%</td>
<td>22.7%</td>
</tr>
</tbody>
</table>

Table 8: National load factors for a typical wind power plant

A slightly different strategy is adopted for the Danish case. The richness of the data on Danish wind turbines allows us to compute an average load factor for each cohort of producers. Data is the Register of Wind Turbines, maintained by the Danish Energy Agency. As the average load factor may be volatile from a cohort to another, we use the polynomial trend in order to not overestimate productivity differences. The evolution of the Danish load factor is given in the figure 9.

Figure 9: Realized versus estimated load factors per cohort (Denmark).
B.3 Economic assumptions and data

B.3.1 Discount rates

The discount rate partially captures the influence of the macro-economic environment on the micro-economic investment behavior. To reflect this causality, yield curves may be used to discount cash-flows. These curves represent the yield from a bond depending on its maturity. The bond that is considered here is a zero-coupon from euro zone AAA rated governments bonds. As a result the discount rate is risk-free, making the RoI necessary overestimated. Yield curves data can be found on Eurostat; 20 years maturity bonds are chosen in order to fit with our assumption on wind farms lifetime. For the Danish case, since the study starts before the Euro implementation, Danish bonds yields are used from 1985 to 1999, the source being MPK100: Government bond yields by country, Denmark statistics.

B.3.2 Loan rates and repayment modalities

For every countries and years we assume that 50 % of the IC are financed through a loan, reimbursed at a market rate on the ten first years of power plant operation. Data on loan rates are the rates for a loan of more than five years from financial and monetary intermediaries to non financial corporations. The European Central Bank provides for this information on an annual basis for each country. Usually, data is not available before 2003, in such a case we assume a 5 % loan rate.

B.3.3 Electricity Prices

The liberalization of electricity markets in Europe that began in the 2000s produced an increasing amount of information. Data on electricity spot price is used whenever it is available, otherwise assumptions on electricity price are made. Sources and assumptions are detailed in the Table 9.

References

Academic literature.


<table>
<thead>
<tr>
<th>Country</th>
<th>Data and assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>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.</td>
</tr>
<tr>
<td>Germany</td>
<td>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.</td>
</tr>
<tr>
<td>France</td>
<td>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 to the wind power.</td>
</tr>
<tr>
<td>Italy</td>
<td>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.</td>
</tr>
<tr>
<td>Portugal</td>
<td>From 2000 to 2006 regulated tariffs are integrated in the RoI. After 2006 yearly average spot prices are used, from the OMEL (Operador del mercado Energéticos). Then after 2012, an assumption of 35 €/MWh is made.</td>
</tr>
<tr>
<td>Spain</td>
<td>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.</td>
</tr>
</tbody>
</table>

Table 9: National electricity prices: data and assumptions


27


Books.


Reports and non-academic studies.


[34] Renewable energy policy review: Germany, 2004.

