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A comparison between American and European wind energy diffusion models

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On the contrary, since for comparing installed wind turbines capacity it is crucial to avoid all plain nuisance factors, we propose to compare the US diffusion model with that of Europe, that is a region similar for extension of geographical area and wind speed. Generalized Bass models were performed to estimate the life-cycle of innovations in the markets of the two regions.

Keywords: renewable energy, wind power, diffusion models, Bass model.

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1 Introduction

It is spreading over the world an enhanced sensibility with respect to environmental problems, like alarming global warming and air pollution, and to energy problems, like oil depletion. The era of fossil fuels is starting out to decline and the next perspectives are not encouraging. The peak of oil in all the major oil exporting-countries (see for instance Guseo & Dalla Valle (2005) and Guseo et al. (2007)) is quite near and it is well-known that, in spite of the more and more sophisticated technological approaches of oil mining, the quantity of oil extracted is lower with respect to expectations and requests. Moreover, air pollution, greenhouse gases, environmental damages caused by the use of fossil fuels for the production of energy and also for other targets (like, for instance, the production of plastic matters) are becoming a serious threat to our health and environment. The energy production, by means of fossil fuels, induces negative externalities because imposes social costs in increased health expenses, in reduced agricultural productivity, in the planet global warming when carbon dioxide or other air pollutants are produced by their burning. We can also include military costs to ensure access to oil, reclamations of polluted sites, destructions of wild habitat.

In this scenario, new sources of energy that are both clean and cost-effective have to be promoted to maintain the same standard of living and to preserve the environment. Wind energy, in particular, is a kind of clean, inexhaustible, readily available energy with the advantage that it aids to reduce greenhouse gas emissions because it does not produce any type of air pollution during its functioning. Moreover, wind power has negligible fuel costs and low maintenance costs, that is low marginal cost and a high proportion of capital cost.

Since wind power is the conversion of wind energy into electricity using turbines, it is convenient to make a distinction between energy produced by wind farms, connected to electrical grids and distributed on large scale, and by small turbines for individual use[1]. This basic distinction together with the importance of the incentive policy to invest in the wind energy sector, that is not economically competitive, become key aspects in this work. We will see, in particular, that different political choices determine a precise response by the investors, causing different trends of investment in this energy market.

The greater obstacle to the development of wind power technology is surely the availability of the wind. It stands to reason that windy places are more suitable than others to be exploited for this renewable energy technology. It was estimated that wind power available in the atmosphere is much greater than current world energy consumption. So, at least theoretically, wind power would be sufficient for our necessities even if, beyond the positioning of sites, other facets are in debate like the transmission lines, the cost of site acquisition, the environmental impact of wind power structure, and the storage of energy produced in excess and not immediately used. With respect to just the latter aspect we point out that technological progresses in this field are very fast: we refer to wind turbines power, that is doubled in comparison to six years ago, and to storage capacity that, though being a crucial obstacle to the development of wind power, is becoming more and more efficient.

The aim of this paper is to model the life-cycle of this renewable energy resource considered as a diffusion process whose purpose is to predict time by time the development of an innovation to understand the dynamics that have characterized its growth, and to detect possible interventions to improve its employment and to make it more convenient. In particular, we refer to a Generalized Bass Model (GBM) introduced by Bass et al. (1994). One of the peculiarity of this modelling is that it is possible to include, in the standard version of the model, intervention variables useful for separating stochastic disturbances from modified systematic life-cycle behaviour. These variables have strictly reference to incentives policies implemented by countries local government and allow to assess the strength of these policies during the observed time of diffusion of the resource. There is an earlier consolidated

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[1] This system is usually used by farms, houses, small business essentially to the purpose of self-consumption.

literature that tackles the problem of modelling a diffusion process. The class of Bass models offers a modelling with a statistical approach obtaining interesting results. See for example, among the others, Guseo & Dalla Valle (2005) and Guseo et al. (2007).

The wind power diffusion processes were analysed and compared for the United States and Europe. At this purpose, very often the comparisons are made between Denmark or Germany and the US, but we believe that the enormous difference of areas makes these comparisons very imbalanced for the European countries. So, to make comparisons, we take into account Europe rather than a single European country.

In particular, Section 2 deals with some international political agreements about the reduction of greenhouses gases, started with the Kyoto Protocol. Section 3 presents data about wind turbine capacity for the United States and Europe. Section 4 presents the basic concepts characterising the class of Bass models, that we have selected to describe the diffusion process of an innovation in a market, together with the details of the non-linear statistical model used and also the adopted method to estimate parameters. In Section 5 we discuss the GBM model estimated for the US wind power, highlighting the presence of two relevant shocks due to a change of incentive policy by the government. In Section 6 is estimated the GBM model for Europe that, on the contrary, presents no shocks. In Section 7 we compare the models, estimated for the US and EU, focusing the discussion on the different types of incentives adopted in the two regions to justify, at least partially, the greatly major installed wind power capacity of Europe with respect to the United States. In Section 8 there are some final considerations about the estimated models, the strong development of renewable energies and the power of political and economical measures in energy sector.

2 Historical background

To understand the dynamics of the diffusion of renewable energy systems it is inevitable to outline the political background that has influenced the energetic questions in these last years: to this scope we profile the key aspects of the Kyoto Protocol, that is a first effort to determine effective measures for reducing greenhouse gases, and of some more recent agreements.

The Kyoto Protocol is the first, and only, binding international agreement that sets targets to reduce the greenhouse gas emissions and entered into force on 16 February 2005 (UNEP, 1997). In this protocol, parties are separated in developed countries (referred to as Annex I countries), who accepted greenhouse gas emission reduction, and in developing countries (referred to as Non-Annex I countries), who have no obligations in greenhouse gas emission reduction. China and India, two of the world's fastest growing polluters, were not included in Annex I countries because they were not the main contributors to the greenhouse gas emissions during the pre-treaty industrialized period. As of November 2007, 175 parties have ratified the protocol that contains legally binding emissions targets for 37 Annex I countries (European Union represents a single party in its own right). As of December 2007, the US and Kazakhstan are the only signatory nations who have not ratified the act. Countries have a certain degree of flexibility in how to respect the emissions targets. An international "emission trading" has established that Annex I countries may buy and sell emissions credits amongst themselves, and non-Annex I countries may sell Carbon Credits to Annex I countries, when greenhouse gas emission reduction projects are implemented in their territory.

The EU has been one of the major supporters of the Kyoto Protocol and has negotiated hardly to persuade hesitating countries. However, some public policy experts argue that the protocol does not go far enough to control greenhouse gas emissions (Niue, The Cook Islands, and Nauru added notes about it when signing the protocol (UNFCCC, 1997)). International treaties must achieve a delicate balance because they have to be politically acceptable; however, those treaties that appeal enough to gain an extensive support often are not effective enough to solve the problems they focus on. By contrast, defenders of the Kyoto Protocol argue that it set the political precedent for more effective greenhouse gas cuts in the future. Following this purpose, the G8+5 group[2] met on February 16, 2007, in Washington at the Climate Change Dialogue. It was agreed that there should be a global system for limiting emissions applying to both developed and emerging countries. The G8+5 group hopes to put this agreement into force by 2009 to supersede the Kyoto Protocol. Indeed, *"to achieve a much bigger reduction in emissions would require immediate policy action and technological transformation on an unprecedented scale"*, since the time is the primary scarcity on facing this problem (IEA, 2007).

What is the position of the United Stated on climate change? The US signed the Kyoto Protocol but has never ratified it. George W. Bush has pointed out that the US will not submit the treaty for ratification, not because the US does not support the Kyoto principles, but because the protocol exempts countries such as China and India. Further, he indicated the uncertainties which he believes are present in the climate change issue. In June 2005, at the G8 meeting the Bush administration expressed a desire for "*practical commitments industrialized countries can meet without damaging their economies*" (Eilperin, 2005). In January 2006, in Sidney, the Asia Pacific on Clean Development and Climate agreement was negotiated by Australia, China, Japan, South Korea and the United States. The pact allows those countries to reduce the greenhouse gas emissions individually, without enforcement mechanism.

However, Bush's policy is not supported by all the local governments: indeed, as of January 18, 2007, 8 local US governments wanted to indirectly apply pressure on the federal government by signing a Regional Greenhouse Gas Initiative. Their goal was to demonstrate that the reductions in greenhouse gas emissions can be achieved even without the ratification of the Kyoto Protocol. As of December 4, 2007, 740 cities in 50 states agreed to the protocol after that public opinion was awakened on this issue.

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[2] It consists of the heads of governments from the G8 nations (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States) and Brazil, China, India, Mexico and South Africa.

3 Diffusion wind data in the United States and in Europe

The production of electric energy through wind systems is one of the ways to respect Kyoto limits. For this reasons, the countries that signed the protocol started to promote incentives policies for the adoption of these new technologies. The United States, although not subscribers of the protocol, is also committed in some way to create renewable electric energy.

Figure 1 (left panel) shows data about the United States yearly cumulative installed wind turbine capacity in Megawatts (points), from 1981 to 2006, extracted from the AWEA web site[3]. The most striking feature of Figure 1 (left panel) is the greater propensity of installed power towards the latter years. Other features can also be extracted: the visual impression suggests a good starting in the adoption process of the wind energy technology in the first beginning of the time series and a stationary behavior in the middle.

The right panel of Figure 1, concerning Europe yearly cumulative installed wind turbine capacity in Megawatts (points), from 1997 to 2006, shows a rapid diffusion of wind power energy among the considered years.

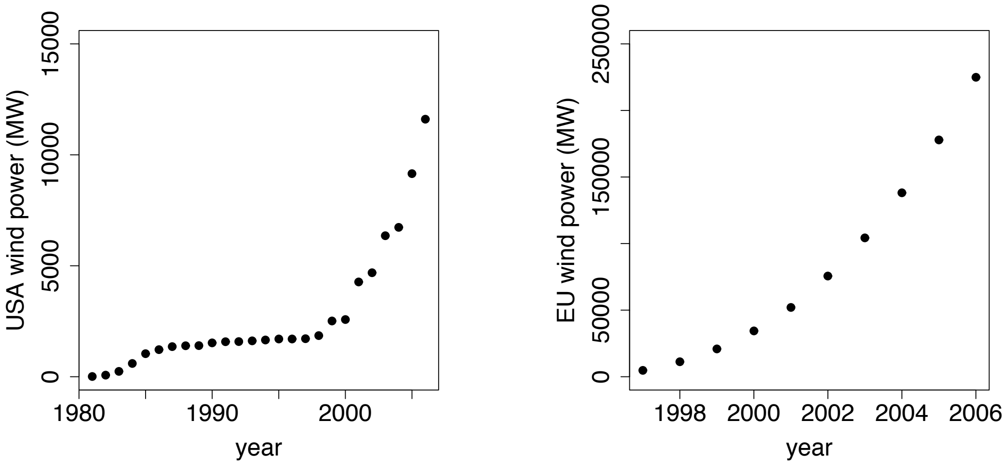

Figure 1: Cumulative American and European wind power data (MegaWatt).

Our aim is to estimate a diffusion model (see Section 4) to assess the evolution of American and European investments in wind energy systems.

4 The Model

In this section we present some basic concepts about diffusion models and in particular about the class of Bass models. The innovation and the perception of this innovation in a social system is fundamental to characterise a diffusion model: time delays or anticipates the adoptions of the innovation among individuals. In this

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[3] American Wind Energy Association: `http://www.awea.org/projects/project_data.html`

case we describe the life-cycle of wind power production with an innovation diffusion model based upon cumulative wind production data in the observed period of time. The assumption at the base of the diffusion model is that the growth of the innovation, here represented by the wind power, is limited. A model that answers to this requisite of saturation is, for example, the generalised Bass model.

According to the model specifications of preceding works related to diffusion models and in particular to the Bass model, see for instance Guseo & Dalla Valle (2005) and Guseo et al. (2007), we specify the structure of the reference model as a non-linear regressive model

$$z(t) = f(\underline{\beta}, t) + \epsilon(t) \tag{1}$$

where $f(\underline{\beta}, t)$ represents the deterministic component that includes also all structural interventions due, for example, to political or economical measures, $\underline{\beta}$ is the vector of parameters and $\epsilon(t)$ is a stochastic process indicating the residual error component. We assume that $\epsilon(t)$ is a process with mean 0, equal variances and incorrelation between different error components, and these assumptions lead to consider a white noise process. In our case, we specify the deterministic component through the Bass model (see Section 4.1) and the Generalized Bass models (see Section 4.2). Furthermore, in Section 4.3 some inferential aspects will be faced.

4.1 The Bass standard model

The Bass standard model (BM) first introduced by Bass (1969) is essentially a function of the potential market considered fixed and of the time. A particularly relevant aspect is that it is possible to estimate the potential market through the first production data. The Bass model in its formulation distinguishes between adoptions due to the innovators and those due to the imitators. Innovators adopt an innovation independently of the decisions of the other members of the social system, and this fact means that the growth of the adoption process does not influence their behavioural choices. On the contrary, imitators are completely influenced by the adoption choices of preceding adopters; they do not adopt the innovation before a certain number of adoptions have been made.

The basic equation of the standard Bass model is the following

$$y'(t) = (p + q)(1 - y(t)) \tag{2}$$

where $y(t)$ is a distribution function of diffusion process, $y'(t)$ is its corresponding density, p and q are parameters referred to quotas of innovators and imitators respectively. Both $y(t)$ and $y'(t)$ are referred to time t and the first one, in particular, is the probability that an event (adoption) happens within t. Since our aim is modelling the number of adoptions occurred within time t, the following cumulative function of adoptions $z(t)$ over time should be considered

$$z(t) = m\ y(t),$$

where m is the potential market or carrying capacity. In this special case, Equation (2) becomes

$$z'(t) = m\left(p + q\frac{z(t)}{m}\right)\left(1 - \frac{z(t)}{m}\right) \tag{3}$$

that can be rewritten as sum of the following two quantities

$$z'(t) = p\,(m - z(t)) + q\frac{z(t)}{m}\,(m - z(t))\,. \tag{4}$$

The first part $p\,(m - z(t))$ is a function of the residual market, $(m - z(t))$, and it is the number of adoptions due to innovators. This component is under the influence of external communication channels, advertising, internal companies information and so on. The second term, that is $q(z(t)/m)(m - z(t))$, refers to the number of adoptions due to imitators and it is related to delayed adoptions due to a word-of-mouth effect: it is, again, a function of residual market with the adjoint of a decreasing rate of penalisation. We expect that for successful innovations the coefficient of imitation q will be larger than the coefficient of innovation p, because the importance of innovators is naturally greater at the beginning of the process and then it tends to decrease monotonically with the time.

It is also possible (see Guseo (2004)) to have an idea of the asymptotic cumulative component of innovators, that have started the diffusion process, by means of the following quantities that is function of only p and q:

$$\frac{p}{q}\ln\left(1 + \frac{q}{p}\right). \tag{5}$$

Ordinary diffusion processes are characterized by an innovator quota usually included between 8% and 36%.

Since Equation (4) is a differential equation, its general closed form solution is

$$z(t) = m\frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}}, \qquad 0 \leq t < +\infty. \tag{6}$$

4.2 The Generalized Bass model

In Bass et al. (1994) there is an interesting development of the model that allows to include exogenous variables $x(t)$ that identify interventions of political and economical nature, that are assumed to have effects on diffusion process.

The analytical form of the generalised Bass model (GBM) is the product of $z'(t)$ of Equation (3) and an integrable function $x(t)$ which oscillates around 1

$$z'(t) = m\left(p + q\frac{z(t)}{m}\right)\left(1 - \frac{z(t)}{m}\right)x(t), \tag{7}$$

while the general closed form solution is

$$z(t) = m\frac{1 - e^{-(p+q)\int_0^t x(\tau)d\tau}}{1 + \frac{q}{p}e^{-(p+q)\int_0^t x(\tau)d\tau}}. \qquad 0 \leq t < +\infty. \tag{8}$$

Model of Equation (7) includes standard Bass model of Equation (4) when $x(t) = 1$, while when $x(t)$ is greater than 1 the adoption process is accelerated over time and, on the contrary, when $x(t)$ is smaller than 1 the adoption process is delayed. It is important to underline that the intervention function modifies only adoption time and neither the potential market nor the innovators and imitators parameters p and q. The intervention function $x(t)$ incorporates exogenous covariates including political measures, economical local provisions and so on. The specification of this function has to be parsimonious with respect to the number of new involved parameters even because for our scopes it is not necessary an exasperate level of detail. A possible choice is to characterise $x(t)$ by means of the effect in terms of duration of time and local strength of the perturbation on the diffusion process (see Guseo (2004), for example).

It is possible to have a simple representation of the intervention function $x(t)$ based on one *exponential* impulse, that identifies very intensive instantaneous shocks which progressively lose their effect time by time. The mathematical form of this exponential impulse is

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]} \tag{9}$$

where $I_{[h_1<t<h_2]}$ is a indicator function assuming value equal to 1 if the shock occurs in the interval $[h_1, h_2]$ and value equal to 0 otherwise, a_1 is the initial temporal point of the beginning of the shock, b_1 expresses how much rapidly the shock decays toward 0 and it is negative, and finally c_1 indicates the intensity of the beginning of the shock and can assume positive or negative sign with respect to the kind of effect of the political or economical intervention.

There is another kind of impulse for intervention function $x(t)$ based on one *rectangular* impulse, like in the following

$$x(t) = 1 + c_1 I_{[a_1 \leq t \leq b_1]} \tag{10}$$

where $[a_1, b_1]$ is the close interval in which a shock may occur, while c_1 identifies the intensity of the effect of the exogenous intervention and can assume both positive and negative values. This impulse begins at time, say, a_1 with a given intensity, keeps holding over the interval length $b_1 - a_1$ and then suddenly disappears.

Therefore, an exponential shock refers to a locally intense intervention that gradually but firmly loses its effect over time, while a rectangular shock identifies an intervention intended to keep unchanged its impact along all the time interval.

A further kind of representation for $x(t)$ pertains to mixtures of different shocks, referring to particular situations in which a series of political interventions have different effects on diffusion models. The mathematical representation of, for example, two successive shocks (exponential and rectangular) is the following

$$x(t) = 1 + c_1 e^{b_1(t-a_1)} I_{[t \geq a_1]} + c_2 I_{[a_2 \leq t \leq b_2]} \tag{11}$$

where the involved parameters are the same of the preceding examples. It is opportune to underline that Equation (11) is purely demonstrative and that any combination of impulses both in number than in typology is theoretically possible.

4.3 Parameter estimation and model selection

To estimate the parameters of the model we use a non-linear least squares estimation method following the algorithm of Levenberg-Marquardt (see Seber & Wild (1989)), verifying that the residuals of the regression are consistent with the assumptions.

In particular, the Durbin-Watson statistic is used to check the autocorrelation of residuals. It is noteworthy to highlight that one of the major troubles that one meets when faces the fit of Bass models is the choice of initial values for parameters to be estimated. A strong experience reached with practical applications helps to hone the sensibility in the choices, because it is well known that the estimation procedures in non-linear regressive models are quite sensitive to small shifts in the initial grid of starting values used for parameters estimation.

When GBM models are performed to evaluate how many shocks eventually affect the adoption process, a model selection procedure must be applied. Let $m_0(t)$ and $m_1(t)$ be models as in (1) with $m_0(t)$ nested within $m_1(t)$: let $\underline{\beta_0}$ be the parameter vector of $m_0(t)$ and let $\underline{\beta_1}^\top = (\underline{\beta_0}^\top, \underline{\beta_\star}^\top)$ be the parameter vector of $m_1(t)$. Model selection corresponds to test the significance of the vector $\underline{\beta_\star}$, at level α:

$$\begin{cases} H_0 & : \quad \underline{\beta_\star} = \underline{0} \\ H_1 & : \quad \underline{\beta_\star} \neq \underline{0} \end{cases} \tag{12}$$

and it is performed with the following test:

$$\frac{(D_0 - D_1)/(df_0 - df_1)}{D1/df_1} \sim F(df_0 - df_1, df_1) \quad \text{if } H_0 \text{ is true} \tag{13}$$

where D_0 and D_1 are the residual deviances of $m_0(t)$ and $m_1(t)$ respectively, df_0 and df_1 are the degrees of freedom of D_0 and D_1 respectively, and F represents the Snedecor's F distribution. If H_0 is rejected at level α, then $m_1(t)$ is significative and it should be preferred to $m_0(t)$. The exact distribution of F-test (13) requires a normal distribution of errors $\epsilon(t)$ and for this reason, in this work, we use F-test (13) as an approximate measure.

5 US wind power modelling

We turn now to the problem of modelling the entire data series of the US from 1981 to 2006. Taking into account the visual impression pointed out in Section 3, we propose a Generalized Bass model with an exponential shock, to explain the probably accelerated growth at the beginning of the time series, and a rectangular shock, to gather the stationarity of the central part (this model will be referred as GB$_{exp+rect}$). In particular, we perform model (1), with equation (8) for $f(\underline{\beta}, t)$ and Equation (11) for $x(t)$.

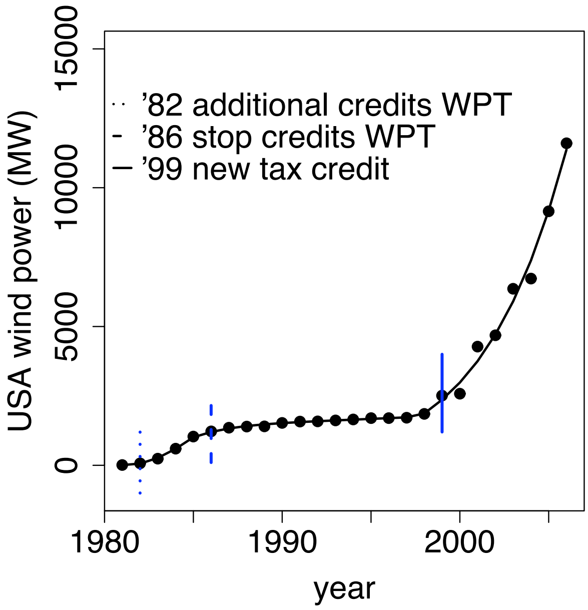
The entire model is identified with a very good fitting ($R^2 = 0.99623$) and residuals are not significantly correlated (Durbin-Watson statistic=2.96437). Estimates, asymptotic standard errors and asymptotic 95% confidence intervals are shown in Table 1, while Figure 2 shows the fitted model. The exponential shock has been detected to be positive ($c_1 > 0$), arising around $(1981 + a_1) \approx 1983$, and its effect was absorbed in time ($b_1 < 0$). The rectangular shock has been detected to be negative ($c_2 < 0$), arising around $(1981 + a_2) = 1986$ and ceasing around $(1981 + b_2) \approx 1999$. Looking at the standard errors and at the width of the confidence intervals, we can say that the coefficients of the two shocks $(a_1, b_1, c_1, a_2, b_2, c_2)$ and the imitators coefficient q are estimated with a certain reliability, but this fact does not happen for the potential market m and the coefficient of innovators p. We think that the model is reliable, but it must be used for short-term forecasts (i.e. 5 years) since diffusion processes need more history to be estimated with accuracy. In fact, it is known that the (Generalized) Bass model provides reliable estimates of m only when the diffusion process has reached a mature state and, even if the wind system has been recorded in the US from 1981, only in the latter years it starts to be more widely adopted because of the policy choices on incentive issue. Furthermore, when incentives are released, the word-of-mouth effect powerfully dominates the behavior of investors making this process characterized by a very low rate p of innovators, whose estimate becomes uncertain, and a high rate q of imitators. Indeed, the asymptotic cumulative component of innovators of Equation (5) is around 0.002%, that is particularly low.

Table 1: Estimates, asymptotic standard errors and asymptotic 95% confidence intervals for the US time series since 1981 (model $\mathrm{GB}_{exp+rect}$). R^2 and Durbin-Watson statistic are also given.

	Parameter	estimate	as. stand. error	as. 95% CI	
	m	112 514	262 102	−440 474	665 502
	p	0.00007	0.00019	−0.00033	0.00048
	q	0.23480	0.03051	0.17042	0.29918
	a1	1.59869	0.54042	0.45851	2.73888
exp	b1	−0.59216	0.22004	−1.05642	−0.12791
	c1	6.47347	4.12862	−2.23718	15.18410
	a2	4.99923	0.86513	3.17396	6.82451
rect	b2	17.71000	0.43289	16.79660	18.62330
	c2	−0.93401	0.06170	−1.0642	−0.80382
	R^2	0.99623			
	DW	2.96437			

At this point, since renewable energy technologies are not economically competitive and their development is strongly affected by policy choices on incentives, we outline the basic points of the american legislation on the renewable energy marketplace of the latter years, in order to understand underlying reasons for the two identified shocks. When wind power production was at the beginning, the Crude Oil Windfall Profits Tax Act (WPT) of 1980 was effective. It increased the energy tax credit of the Energy Tax Act of 1978 (ETA) and, furthermore, these additional credits were extended from December 1982 to December 1985 for some renewable energy technologies, as the wind power system. Investors probably believed in this clean way of producing electric energy and this fact led to a rapid increase of the production in those years. Unfortunately, in 1986, while the business energy tax credit was extended for some renewable energy systems, such as solar and geothermal, it did not happen for the wind power system. In 1992 the Energy Policy Act established a production tax credit (PTC) that penalized again the wind power system, with respect to solar and geothermal systems. Therefore, from 1986 the wind

Figure 2: The points correspond to cumulative US wind power data (MW) and the line to the fitted $\mathrm{GB}_{exp+rect}$ model.



power system was not economically supported by any significant energy tax and the adoption process became stagnant waiting for new incentives. Only in 1999 the Tax Relief Extension Act extended, for wind power, the PTC of 1992 until the end of 2001 and this fact enabled the wind power adoption process to start again. However, since that time, only short term PTC extensions are passed and, consequently, the adoption process has become a "boom and bust" cycle. In fact, since the end of 2001 credits were extended only in March 2002 for 2 more years, and the late renewal caused the adoption reduction occurred in 2002 (bust), with respect to 2001 (see Figure 2). In 2003 investors started to invest again (boom), while implementation of planned projects slowed down dramatically in 2004 for, again, a late renewal of PTC. After 2004 a major attention has been payed in renewing PTC to control this "on-again/off-again" status, but only a long-term PTC will provide the industry with more stability. The two identified shocks seem to be the effect of policy choices on incentives: in particular, the exponential shock starts when WPT extended ETA tax credit from 1982 to the end of 1985, and the rectangular shock lies in the time interval (1986-1999) where there were no specific incentives for the wind (see Figure 2).

We decide to test if the growth of the first years is so accelerated to be explained by an exponential shock. Table 2 shows the results of nested model test (13) to assess the significance of the exponential shock at level $\alpha = 0.05$ of significance. Referring to hypothesis test (12), $m_1(t)$ corresponds to $\mathrm{GB}_{exp+rect}$ model and $m_0(t)$ to the nested GB_{rect} model with only the rectangular shock. In particular $\underline{\beta_\star}^{\mathsf{T}} =$

(a_1, b_1, c_1) corresponds to the parameter set of the exponential shock. Evaluated F-test corresponds to 16.88 and p-value to $2.41 \cdot 10^{-5}$: the results express a huge evidence of rejecting GB_{rect} in favor of $\text{GB}_{exp+rect}$, confirming the hypothesis of an accelerated growth for the WPT additional credits in 1982-1985.

Table 2: Nested model test among $\text{GB}_{exp+rect}$ and GB_{rect} models.

Model	Residual Deviance	Degrees of Freedom	F-test	p-value
$\text{GB}_{exp+rect}$	244.95	17		
GB_{rect}	974.92	20	16.88	$2.41 \cdot 10^{-5}$

6 EU wind power modelling

In this section we fit model (1) with Equation (6) for $f(\underline{\beta}, t)$, for data provided by AWEA concerning Europe yearly cumulative installed wind turbine capacity in Megawatts (points), from 1997 to 2006. Inspection of Figure 1 (right panel) highlights a continuous growth of adoptions in the observed time period. Clearly, we observe only a time slot of a process that has begun formerly but whose significant history is recent. At first sight, it seems not to be present exogenous interventions such to modify the adoption system, so it could be appropriate to fit a standard BM model, at least at the beginning of the analysis. The results are in fact quite good because, as it is possible to see from Table 3, the model has a very high goodness-of-fit very near to the saturation ($R^2 = 0.9999$). Analysing the residual component of the estimated model we can establish also that there are no significative correlations among residuals (Durbin-Watson statistic= 1.44126). Moreover the estimate of the potential market m is well centred and the 95% asymptotic confidence interval is quite small. Looking at the last cumulative observation in EU data ($z(2006) = 224\,858$) and comparing with the estimate of potential market of the BM model ($\hat{m} = 528\,191$) we can gather that the wind power life-cycle has been arrived to a stage a little lower than the half (42.57%).

Table 3: Estimates, asymptotic standard errors and asymptotic 95% confidence intervals for the EU time series since 1997 (BM model). R^2 and Durbin-Watson statistic are also given.

Parameter	estimate	as. stand. error	as. 95% CI	
m	528 191	32 874	450 457	605 926
p	0.00805	0.00031	0.00733	0.00878
q	0.34171	0.00945	0.31936	0.36407
R^2	0.99990			
DW	1.44126			

With respect to the estimates of parameters p and q we can observe that the estimated quotas of imitators is quite relevant, while the estimated quotas of innovators is very low and this evidence can be justified by the kind of innovation technology analysed here. In the wind power energy sector, an investor has to be willing to have a return of the investment even ten or fifteen years later the beginning of the financial venture and this fact is clearly not very popular. Moreover, the next possible profits are reached in a context that is in continuous movement and that does not depend by the choice of a single investor but by a complex scenario which depends by technological progress, availability of resources, political regimes, choices of economical policy, social taking offices, environmental safeguard and so on. According to this preamble, the investments in renewable energies can be considered a bet made by only a few brave investors, at least at the beginning of the process. Having a look at the rate $q/p = 42.42944$, we obtain that the asymptotic cumulative component of innovators (5) is around 6.78% that it is low. So, we deduce that the diffusion process of wind power energy is heavily driven by a strong imitative component.

Forecasts for EU wind power production for 5-years are visible in Figure 3 (solid line), whose comment and interpretation is matter of next Section 7.

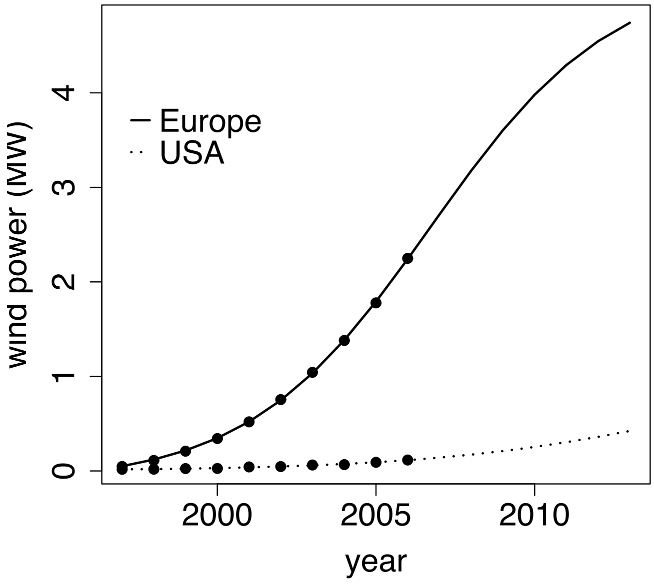
7 United States versus Europe

In Sections 5 and 6 we tackled the problem of modelling the diffusion wind power process for the United States and Europe separately. A common evidence is that the innovators are flatly less than imitators. This fact, on one hand, is surprising because usually, at the beginning of the process of innovation diffusion, the component of innovators has a great importance while only afterwards the number of innovators decreases. On the other hand, the quota of innovators, that is particularly low in this case, is affected by the uncertainties of investments in the energy sector. Beyond this evidence, the US innovators are much fewer with respect to the EU innovators, and this fact is comprehensible in the light of the unsteadiness and uncertainty of the incentive policies of those years in US, discussed in Section 5.

The US has a great chance of producing electricity from wind and this great potentiality should be exploited. Short-term forecasts for both areas, using $\mathrm{GB}_{exp+rect}$ for the US and BM for EU, are shown in Figure 3. The exacerbated difference between the two diffusion processes is strikingly evident and the US, if compared to EU, is still at the beginning of the diffusion process. An aspect useful to justify, at least partially, the gap between the US and EU is the awareness of the different incentives policies adopted in the US and in more than 25 countries in EU. Nowadays, in Europe there are three categories of incentives: “Fixed Tariff Systems”, with about ten years of duration adopted by Denmark, Germany, Spain and Italy, “Concession Systems” such as Non Fossil Fuel Obligation of England and the competitive bidding adopted by France, Ireland and Scotland and finally incentives like “tax breaks”, “green electricity”, “carbon taxes”. The first incentives system, called also Feed Laws, appears to be the most effective since the mentioned countries have produced more electricity than any other country. This system allows the interconnection of renewable sources of generation with the electric-utility network and specifies a price that is paid for every kilowatt-hour produced. For example, in Italy, a local project gives 0.30 Euro for every Kilowatt produced even by a small producer along a period of 15 years from 2008 and this is a strong signal by the government to promote wind energy production. It is never so easy to convert one of the schemes from one country to another, but theoretically if there were favourable legislation and general acceptance, an incentive system as the Feed Laws could be very successful, because it safeguards developers, owners and financiers.

The incentive policy in the United States is quite different. To promote wind energy development, the United States provides tax credits based on installed capital costs. From the beginning of 1990 in advance the tax credits were instead based uniquely on the sale of wind-generated electricity: this mechanism has eliminated from incentives small consumers willing to produce electricity for self-consumption. This questionable incentive policy that leads to a centralisation of the technology in the hands of a few, is used only in the US. Many american people and associations believe that Tax Credits should be converted into some form of Feed Laws to develop the wind adoption process as in Europe, and try to put pressure on the government on this topic.

Figure 3: Points represent cumulative wind power data (MW rescaled by 10^5) and lines the short-term forecasts for the US ($\mathrm{GB}_{exp+rect}$ model) and Europe (BM model).



8 Conclusions

In this paper we have studied the diffusion of a clean technology to produce energy by wind power and we have provided short-term forecasts about its oncoming evolution. We have compared wind power installed capacity of the United States with that of Europe, instead of the more representative European countries (Germany and Norway, for example), because we believe that a more well-balanced comparison should consider the geographical extension of countries, that for the US and EU can be considered quite similar.

A set of remarks of notable interest is emerged in this study.

First of all, in general, it is an incontrovertible evidence that wind power as any other clean energy, needs of a steady and strong political and financial support to be adopted on energy markets. In fact, for each analysed data, it is noteworthy that when incentives policies run out, then a rapid fall down of investments occurred: so, the emptiness of financial support by governments determines directly the lack of adoptions.

With respect to the US data, the estimated GBM model has highlighted the presence of two different interventions (captured by an exponential and a rectangular shock), which explain an accelerated start of the adoptions sustained by a strong incentive policy from 1982 to 1985 and then a long phase of stationarity due to a stop of government financial supports till 1998; whereas, for EU data a BM model (without exogenous interventions) was estimated. By comparing the two models, it arises that the US has a great potentiality in producing electric energy from wind power and that the great discrepancy, with EU, depends heavily from the incentive policy which has eliminated contributions to small consumers for self-consumption. In fact, the wind power capacity installed in the US is always largely under the installed capacity of EU, during the same period, and in this case the choice among different types of incentives becomes fundamental.

A common evidence between EU and US diffusion models is that the innovators are flatly less than imitators, and it is a situation compatible with uncertain investments and unstable government measures. However, the quota of innovators is much smaller for the US and the reasons lye in the uncertainties and hesitations, that we have already discussed, of the US government to take measures oriented to adopt wind power technology.

Finally, the wind power scenario in the United States and Europe described by our models is well-drawn and detects that, if governments believe strongly in renewable energies supporting economically the investments of the pioneering investors, then the propensity to invest in clean energy by people becomes strong. If the awareness by the governments of the importance of finding quickly (clean) alternatives to fossil fuels become a urgent need, then it will be a first step to warrant a good quality of life for all of us.

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