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Capacity factor of wind power realized values vs. estimates

Nicolas Boccard

Departament d'Economia, Universitat de Girona, 17071 Girona, Spain

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ABSTRACT

For two decades now, the capacity factor of wind power measuring the average energy delivered has been assumed in the 30–35% range of the name plate capacity. Yet, the mean realized value for Europe over the last five years is below 21%; accordingly private cost is two-third higher and the reduction of carbon emissions is 40% less than previously expected. We document this discrepancy and offer rationalizations that emphasize the long term variations of wind speeds, the behavior of the wind power industry, political interference and the mode of finance. We conclude with the consequences of the capacity factor miscalculation and some policy recommendations.

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1. The capacity factor puzzle

1.1. Capacity factor matters

Voters attitude in the EU toward the environment and the threat of climate change has led their elected representatives to take action to reduce human made carbon emissions; ambitious binding targets have been set for the share of renewable energy sources (RES) in the electricity mix. The US and other OECD countries are on the verge of adopting similar measures. This, in itself, indicates that the marginal social value of further reductions is greater than its marginal cost (at least in affluent societies). The contribution of a RES to carbon emission reduction is the product of electricity output by the carbon content of the current fuel mix (typically computed at country level). Since fuel mix evolves slowly, we may assume it to be constant in a first approximation.[1] Eventually, the social value of a RES is simply its yearly output and in turn output is the product of installed capacity by capacity factor.

Installed capacity, whether computed at the region, state or country level is the most widely disseminated information regarding an electricity generation technology, be it wind, hydro or nuclear, mostly because it is readily understandable to voters. It is thus natural that a technology lobby communicates on this aspect in order to maintain political support and subsidies (in whatever form they come). Likewise, public authorities emphasize capacity installation as a display of implementation of the policies they previously committed to (e.g., Kyoto targets for carbon emissions). The capacity factor is a less intuitive indicator that measures the economic (not physical) efficiency of a technology and therefore matters for cost calculations but also, and this is the point we raise here, for the overall achievement of carbon reduction objectives.

Large hydropower has been the main RES contributor for most of last century but its development has considerably slowed in developed countries due to the exhaustion of adequate sites and above all to the political opposition to its environmental impact. Over the last two decades, wind powered generation (WPG) has proven to be the most economical alternative to raise the share of RES in the electricity mix; it has already captured a significant quota in numerous countries and is bound to rise further (given the aforementioned public policies). For this particular technology, and essentially all RES, marginal cost is close to zero so that the levelized (average) cost of output is inversely proportional to the capacity factor.[2] Good knowledge of the WPG capacity factor is then crucial for both private and public decision makers.

Indeed, a private investor cares for total profit thus for WPG output. To compare projects of similar size (in terms of capacity) one thus relies on the rate of return which in this case is proportional to the average capacity factor over the 20 years

E-mail address: nicolas.boccard@udg.edu

[1] However, as the RES share of electricity output rises, the carbon content of the fuel mix decreases so that additional RES becomes less efficient (in terms of cutting emissions).

[2] In the absence of variable cost, average cost is the ratio of fixed cost by yearly output where the latter is proportional to the capacity factor.

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lifetime of the equipment. Likewise, the public decision maker is supposed[3] to design RES support schemes with a view to efficiently use taxpayers' money, i.e., to obtain the greatest amount of carbon emission reduction per monetary unit levied, so that once again capacity factor is the central concern. Beyond their environmental objectives, RES also help to reduce the dependence on fossil fuel imports, i.e., the more efficient is WPG in a country, the more energy independent it becomes. We may thus conclude that capacity factor information is valuable for all sides dealing with wind power.

1.2. Local observations

Before delving into empirical studies, the concept of *capacity factor* must be pinpointed beyond the intuitive ratio of realized over potential output. The scope can range from a single turbine to the entire population (at world scale) going through regions, countries or classes such as offshore/onshore or plain/mountain. Unlike some controllable technologies that are able to run all day long (except for failures), wind turbines depend on intermittent wind to produce electricity. The daily capacity factor is thus likely to vary greatly from one day to another. In order to get a constant value characterizing adequately the technology under scrutiny, the duration of observation must be large enough to smooth out temporal variability, e.g., one year or, even better, one decade. When computed over such long periods, capacity factors become completely independent of the intermittency phenomenon which is therefore not considered in this article.[4]

It must be noted from the outset that the capacity factor of a wind turbine can be set at any level between 0% and 100% by an appropriate choice of rotor and generator size.[5] However, to each geographical location corresponds a single combination of rotor and generator size that maximizes yearly energy output (over the long run). As we already argued, this is the optimal choice for a developer (whether private or public). We can thus safely assume that every working wind turbine is actually designed this way. From this point on, the capacity factor of a wind turbine becomes an exogenous value entirely dependent on its geographical location.

The academic literature on capacity factors is not large. We searched the Elsevier, Wiley and Springer databases for "capacity factor" AND "wind power" and gathered results synthetically in Table 1. Letter codes are G for global (country) scope, L for local scope, T for theory and the ISO 3166 country code. Most studies use computational models applied to records of wind speed data at specific locations; a few use wind power output from sample farms to extrapolate to larger areas. We report the capacity factor estimates. Although some low measures are recorded, the general picture is a rather high capacity factor; for instance, table entries average at 37%.

It is interesting to note that studies geared at computing the wind power energy potential at earth level rely on more realistic capacity factors: Grubb and Meyer (1993), World Energy Council (1994) and Hoogwijk et al. (2004) used, respectively, 22.5%, 25.1% and 26.5%.[6]

Table 1
Capacity factors estimates.

• Nfaoui et al., 1991: 33%, L, MO	• van Wijk et al., 1992: 22%, L, NL
• Wood, 1994: 55%, L, NZ	• Cavallo, 1995: 60%, L, Ka, US
• Salameh and Safari, 1995: 35%, L, JO	• Cataldo and Nunes, 1996: 40%, L, UY
• Abed, 1997: 40%, T	• Iniyan et al., 1998: 19%, L, IN
• Iniyan and Jagadeesan, 1998: 25%, L, IN	• Jangamshetti and Rau, 1999: 29%, L, IN
• Pryor and Barthelmie, 2001: 25–51%, L, DK	• Lu et al., 2002: 39%, L, HK
• Chang et al., 2003: 45%, L, TW	• Teetz et al., 2003: 49%, L, AQ
• Doherty et al., 2005: 31%, L, IE	• Jaramillo et al., 2004: 51%, L, MX
• Rehman, 2004: 38%, L, SA	• Abderrazzaq, 2004: 24%, L, DE
• Bird et al., 2005:38%, L, CA, US	• Denholm et al., 2005: 46%, L, ND, US
• Ilkan et al., 2005: 35%, L, CY	• White, 2006: 20–29%, L, MN, US
• Ahmed Shata and Hanitsch, 2006: 53%, L, EG	• Inoue et al., 2006: 17–45%, L, JP
• Caralis et al., 2008: 27–30%, G, GR	• Sahin, 2008: 30%, G, TR

1.3. Global realizations

Public information disclosure on capacity factors by non-academic stakeholders such as the wind lobby, public agencies or transmission system operators (TSO) is at best thin. In this article, we gather all the information on wind power capacity (GW) and output (TWh) appearing in public reports and websites to compute time series of capacity factors across countries.

Our main reference is the *wind energy barometer* of think-tank EurObserv'ER with corrections from more reliable sources, whenever available.[7] While there are only minor revisions regarding installed capacity from year to year in all sources, generation data show important discrepancies, both between yearly reports of the same source and between different sources. We have favored the most recent reports and those of TSOs over research institutes.[8]

As we are ultimately interested by the large scale deployment of WPG, we limit ourselves to countries where wind power represents more than 1% of total generation capacity. Table 2 displays the actual records of WPG in European countries ordered by currently installed capacity. The first three lines indicate installed capacity at the end of 2007, output for 2007 and the share of load served by WPG in 2007. The bottom line is the arithmetic mean of the five yearly capacity factors over the 2003–2007 period. We limit ourselves to this time span to enable the inclusion of a maximum number of countries. To account for the continuous development of WPG, we use the mid-year average installed capacity; this yields greater capacity factors than with the ratio of output to end-of-year capacity.

The average European CF over the last five years is less than 21%. Compared to the popular 35% value, WPG is $\frac{35}{21} - 1 \simeq 67\%$ more expensive and contribute to $1 - \frac{21}{35} \simeq 40\%$ less tons of carbon emission reduction than previously idealized (whatever the carbon content of the European fuel mix). Even if we settle with the little publicized 24% claim made by the European wind power lobby for a "normal wind year" at the current level of development (cf. EWEA, 2008, p. 29), the cost increase is still 15% while the carbon underachievement is still 13%.[9]

[3] The conditional is used to reflect the opposite stances of the "public interest" and "public choice" theories of state intervention; both views hold support among academia.

[4] Our companion paper (Boccard, 2008) contributes to the debate on the intermittency issue.

[5] A large rotor combined with a small generator requires only a low wind speed to function. It thus runs most of the time and achieves a very high CF; this is obviously at the cost of a low yearly energy output.

[6] We convert their full-load hours assumption into CFs.

[7] Publications from the wind power lobby are of little use since they never mention energy output (e.g., EWEA, 2007a or GWEC, 2007 do not feature the word "GWh" used to measure electrical output).

[8] For the UK, we use (BERR, 2008); for Spain, reports from the TSO REE; for France, the report by France Energie Eolienne; for Germany reports from research institute ISET.

[9] In terms of full-load hours, CFs of 21%, 24% and 35% correspond to 1840, 2100 and 3070 h.

Table 2
Average capacity factors over 2003–2007.

Area	EU15	DE	ES	DK	IT	UK	FR	PT	NL
Capacity (GW)	56.3	22.2	14.1	3.1	2.7	2.5	2.4	2.2	1.7
Energy (TWh)	97.7	39.5	28.8	6.1	4.2	5.3	4.2	3.8	3.5
Load share (%)	3.2	6.2	8.5	15.6	1.3	1.3	0.7	7.0	3.3
Capacity factor (%)	20.8	18.3	24.8	22.8	19.1	26.1	22.3	22.7	21.5
Area	AT	GR	IR	SE	BE	PL	FI	CA	US
Capacity (GW)	1.0	0.9	0.8	0.7	0.3	0.3	0.1	2.4	16.6
Energy (TWh)	2.0	1.9	1.9	1.2	0.5	0.5	0.2	4.4	32.1
Load share (%)	3.1	2.9	16.2	0.8	0.5	0.3	0.2	1.9	0.7
Capacity factor (%)	20.1	29.3	29.3	21.7	20.0	25.9	21.8	22.4	25.7

Realized capacity factors oscillate across time and regions in the 20–30% range. The higher end is found in Greece, Eire (Rep. of Ireland) and the UK all of which benefit from numerous windy costal areas with low density of population that enable effective sitting in those preferable zones. The contrast between low and high CF regions of a single country is developed in Section 4.3.

For reference, Table 2 includes the United States at federal level (US) and California (CA), the state with the longest experience in WPG.[10] Regulatory commissions in the other states with large wind power deployment do not seem involved with WPG so that no information is disclosed. The Energy Information Administration (EIA) collects monthly data from the 40% largest plants (all technologies included) and estimates generation data for the remaining 60%.[11] The resulting CF at the US level is in stark contrast with AWEA's (2005) claim that 35% is a typical capacity factor for the US. Likewise, Bolinger and Wiser (2009) use the EIA dataset to display the 2007 CF according to the year of installation of turbines. Although the average over the different classes is not provided, the impression one gets from looking at their Fig. 12 is that the US CF was above 30% in 2007. Yet, the very same data source indicates a global US CF of 26%.[12] The discrepancy between realized and anticipated performance is already being inquired in workshops AWEA (2008a, b) (we thank a knowledgeable referee for pointing out these).

The strongest discrepancy between theory and realized values regards the large scale deployment of offshore WPG. Academic reports regarding the UK by SDC (2005), Gross et al. (2006) or Sinden (2007) borrow the 35% capacity factor at the 2020 horizon adopted by Dale et al. (2004). The later authors justify their choice on the grounds that the UK wind resource is excellent and that half the capacity will be offshore. While the first statement holds in relative terms, it is debatable in absolute terms. Indeed, Table 2 indicates that WPG in the UK is 25% more productive than the EU average, but since the later is very low, the UK CF ends up being moderate and still far from the 35% theoretical level. Secondly, given the 27.5% long term CF average for current onshore capacity in the UK,[13] future offshore wind power would need to reach a 43% CF to achieve the overall 35% mark. This goal will be hard to reach given that the 2003–2007 average CF for offshore is 26.5% (cf. Table 7.4 in BERR, 2008). The more recent opinion by BWEA (2006) (cf. Table 1, p. 16) proposes a more conservative goal of 30% CF for onshore and 35% for offshore.

At the European level, the recent vision offered by EWEA (2008) assumes that by 2020 capacity factors will reach 29.6% for onshore and 44.6% for offshore.[14] Oddly enough, in EWEA (2007b), published months earlier, the future offshore CF is set at 40% (cf. footnote 8, p. 8). The discrepancy with the 44.6% value simply reflects the absence of hard information on which to base an estimate, forcing authors to make unsubstantiated guesses. Comparing the future onshore CF with current level means that repowering, better sitting and improved design of wind turbines are excepted to increase overall efficiency by $\frac{29.6}{20.8} - 1 \simeq 42\%$ in just over a decade. This is by no means a small feat.

In our opinion, capacity factors (at country level) above 30% for onshore and above 40% for offshore are mere leaps of faith lacking the support of WPG measurement data and a proper model of the learning curve able to deliver on those promises. They should be properly revised using the wealth of information that is starting to emerge out of stakeholders reports and data disclosure policies.

2. Wind variability

In this section, we first report on wind indexes, an effort to track the variations of wind at the decade level which explains part of the capacity factor puzzle. We then present some very long term meteorological data that help understand how beliefs about high CFs could be sustained up to now.

2.1. Wind indexes

The long term distribution of wind speeds is known to depend on meteorological phenomena whose duration is of the order of the decade. Capacity factors based on yearly output do not reflect the long term potential of a region because they are likely to evolve. For that reason, a low observed capacity factor may be due to unusually low winds, below their long term potential. Several research institutes from countries bordering the North Sea measure the long term variations of wind speed and produce a *wind index* which is basically the ratio of current monthly output to the long term average (cf. Windmonitor for Germany,[15] EMD for Denmark,[16] Garrad Hassan for the UK,[17] WSH for the Netherlands and Elforsk for Sweden). The longest range of data comes from Denmark. Fig. 1 displays the Danish monthly wind index alongside its long term average at 100. Although monthly index values differ among countries, one can see in Fig. 2 that their yearly averages nevertheless evolve in parallel fashion (as already shown by Atkinson et al., 2006).

We use the yearly wind indexes to correct the observed CFs in each country. The average of the CF over the last decade increases from 24.3% to 25.5% for Denmark, from 18.6% to 18.9% for

[10] As of December 2008, the California Energy Commission discloses wind power capacity and output up to 2006. Our 2007 energy figure uses an estimate corrected for overstatement in the previous years.

[11] Large variations from some of the main WPG respondents make the confidence interval of the CF estimate quite large. Overall, the quality of US data is below par when compared to the EU.

[12] Total US WPG output was 32143 GWh in 2007 (cf. EIA) whereas mid-year capacity was $\frac{16904+11575}{2} \simeq 14239$ MW (cf. AWEA's project database); hence the CF was $\frac{32143}{14239\times 8.760} \simeq 26\%$. Over the 2007/09–2008/09 period, output was 41248 GWh while the average capacity was $\frac{16824+18303+19549}{3} \simeq 18225$ so that the CF remained the same.

[13] This value is greater than the one found in Table 2 because a decade of data is used.

[14] As usual, capacity factors are not disclosed. We thus compute the ratio of expected TWh output by the expected GW capacity shown, p. 30, i.e., $\frac{467}{180\times 8.76}$ and $\frac{469}{120\times 8.76}$.

[15] The denominator for the index is the average WPG output computed from wind speed series at five locations over the 1950–2000 period.

[16] As explained in Nielsen (2004), the 1976–1978 average is initially used as the denominator for the index starting in 1979; from then on, periodical readjustments take place (cf. data file). We use the raw data covering the 1979–2007 period. As the mean is 97.4, a rescaling is performed to produce a mean of 100.

[17] Same as Denmark using the 10 year average previous to the year being computed.

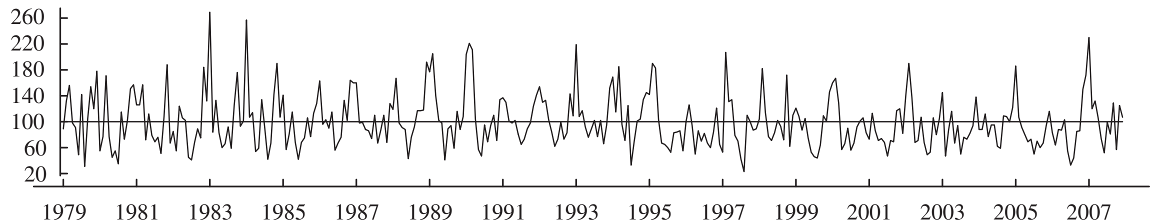

Fig. 1. Danish monthly wind index.

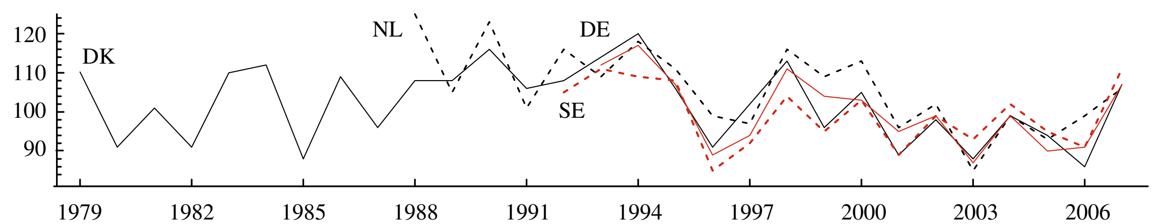

Fig. 2. Northern Europe yearly wind indexes.

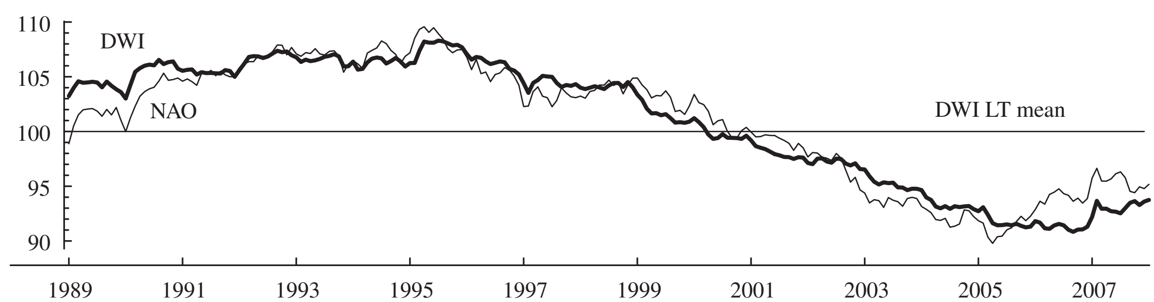

Fig. 3. NAO index vs. Danish wind index.

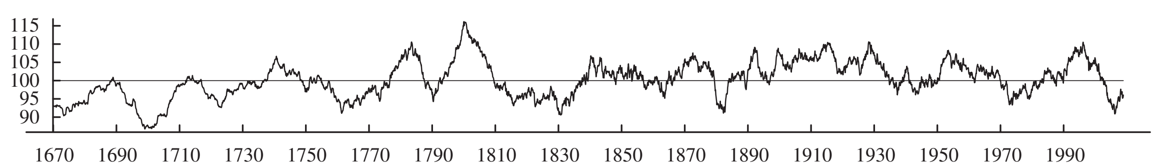

Fig. 4. Long term change in the NAO index.

Germany and from 20.9% to 21.9% for the Netherlands. As a mind experiment, we apply the Danish index (the most reliable) to the EU-15 data over the 2003–2007 period; this correction increases the CF from 20.8% to 22.5%. We may thus conclude that the wind speed potential must be taken into account, though its impact is not as great as the wind lobby pretends. For instance, the German Wind Energy Association (BWE) uses a potential WPG output measure that amounts to an implicit wind index which is artificially set at 20% below the real German wind index computed by research institute ISET.[18]

2.2. Long term wind evolution

Atkinson et al. (2006) show that the North Atlantic oscillation (NAO) is a good approximation to the wind indexes of Northern Europe over the period 1990–2005. Our extension to the 1979–2007 period confirms their findings. Our procedure is as follows. We first scale the monthly NAO series by a factor 1000. We then run a least-squares fit of the Danish Wind Index (DWI) over the 10 years moving average of the NAO index.[19] Lastly, we use the intercept 96 and slope .0288 to rescale the NAO index.[20] Fig. 3 displays the 10 years moving average of the DWI (bold curve) together with the rescaled 10 years NAO moving average (and the mean of the DWI at 100).

Three decades can be deemed the long term in economics but it is a rather short period for atmospheric oscillations and thus for wind speeds. This is illustrated in Fig. 4 displaying the monthly values of the 10 years moving average of the NAO index over three

[18] The ratio of real to potential output is an implicit wind index whose average over the last 15 years is 80% whereas the "true" German wind index averages at nearly 100%.

[19] As we use monthly values, this is a moving average over 120 data points.

[20] Over 3 centuries, the NAO mean is $\mu = 31$ while its coefficient of variation is $\gamma = \mu/\sigma = 48\%$; for the 10 years moving average, we find $(\hat{\mu}, \hat{\gamma}) = (37, 5\%)$. Over the shorter 1979–2007 period, we have $(\mu, \gamma) = (44, 41\%)$ and $(\hat{\mu}, \hat{\gamma}) = (96, 2\%)$. The correlation between the monthly NAO and DWI is $r = .49$, reaching $\hat{r} = .96$ when using the 10 years NAO moving average.

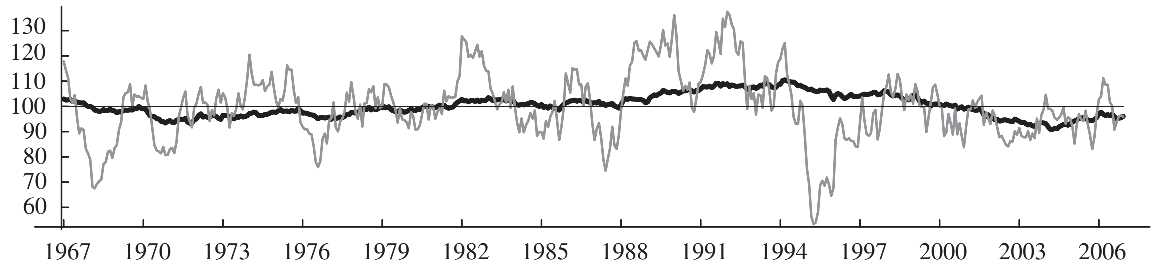

Fig. 5. Recent change in the NAO index.

centuries.[21] One clearly sees a rise of the NAO starting around 1970 and lasting two decades. Upon observing that the average yield of wind turbines was increasing during these two decades, a practitioner would have been right to exclude "long term wind surge" as a possible explanation as it was and still remains a low probability event. Technology improvement was therefore a more plausible cause. This might have unduly reinforced the belief put onto the learning curve effect (cf. Section 3.2). Fig. 5, by concentrating on the last four decades, warrants this opinion. We see how the one year moving average, displayed in gray, varies widely, making a surge or decline impossible to anticipate. We only know about it once it is over. After 1993, the index went downward for a decade and reverted below its long term average (shown at 100).

3. Human factor

In this section, we relate the capacity factor puzzle to the behavior of the wind power industry. We deal with the inefficient packing of turbines on farms, the excessive hopes put on the learning curve and the selection bias characterizing the community supporting wind power at large.

3.1. Shadowing

This physical phenomenon originates from the fact that wind farms compromise optimal distance between turbines to save on land cost or to pack many turbines over a high quality area of limited extension.[22] This claim is easily proven.

We may say in a first approximation that the capacity factor is a decreasing function ρ_n of the number n of turbines per square km that is flat until the threshold level $\bar{n}$ where shadowing starts to bite. At country level there is no shortage of windy sites, so that the (socially) efficient packing density is $\bar{n}$.[23] The situation for a private developer is different because at the outset of the adjudication procedure, he receives a piece of land of fixed size so that his interest reduces to profitability per square km. The latter being $n\rho_n$, the optimal choice is n^* such that $\rho_n + n\dot{\rho}_n = 0 \Leftrightarrow \dot{\rho}_n = -\rho_n/n < 0 \Rightarrow n^* > \bar{n}$, i.e., the private choice is excessively large, leading to a reduced capacity factor for the farm, as a whole. Much like the over-exploitation of open access natural resources, shadowing is an instance where private and public incentives are mildly but not exactly aligned.

As reported by Kaltschmitt (2007, p. 331), the output of a wind farm is on average 92% of its nameplate capacity, i.e., although a single 2 MW turbine can yield 2 MW under a large span of wind speeds, a 50 turbines farm will never yield the nameplate capacity of 100 MW but 92 MW at most. If the packing behavior at the origin of shadowing could be eliminated, the European capacity factor would rise from 21% to 23%, i.e., a 10% compensation.

3.2. Learning curve

The learning curve is the general process of human activity by which past experience in production helps to improve the quality of future units and reduce their cost. However, the rate at which standardized cost decreases every year tends to flatten as the product comes closer to industrial maturity. In the case of wind power, learning applies to turbines production, sitting, connection to the grid and maintenance. The main gain for WPG is the reduction of the capital cost[24] since capacity factor improvement is limited to better design of turbines and improved sitting.

Up until 2000, California was the one of the few regions publicizing aggregate information regarding its wind power program. California Energy Commission (2001, p. 15) reported how the state capacity factor grew from 13% in 1985 to 24% in 2001, a clear indication that the learning curve was at work for WPG during the 1980s and 1990s.[25] Over the last decade, the wind power industry has noticed an even stronger development which had the potential to harness further learning thus capital cost reductions and capacity factor improvements. As we have previously shown, the 1980s and 1990s were also a temporary, yet unusually long, period of rising wind speeds that may have compounded with expected gains from learning to produce the incorrect belief that the aggregate CF would keep rising toward its theoretical limit, the CF at the best site in the territory under consideration. This did not happen because averages usually do not converge to the maximum of the sample. The California CF, for example, decreased since 2001.

3.3. Selection bias

We draw here the well-known psychological human bias according to which we overemphasize the relevance of events comforting our views and, logically, ignore those prejudicial to us. This bias is clearly present in the writings of the wind, nuclear or

[21] We first apply the previous fit parameters to rescale the NAO index. Since its mean is 99, we further adjust it to have a 100 mean. As a by-product, we may say that Danish wind force over the last three decades was 1% above its very long term average.

[22] Similarly, sitting a wind farm nearby an HV line or a road enables to save on connection cost and maintenance.

[23] It is only when first class wind sites become scarce that the government must decide whether to pack more turbines per farm at top sites or develop new farms at subpar locations.

[24] There most detailed information relative to the learning curve for WPG is related to the turbine cost which account for 3/4 of the total. Wiser and Bolinger (2007) found a 2.4% yearly cost reduction for the US over the 1982–2004 period and a slight increase since then. According to English study SDC (2005), the price of wind turbines fell by 3.7% per year over the 1990–2004 period. A German study indicates 2.3% yearly reduction.

[25] In retrospect, such low figures are also an indication that the first large wind farms were chosen without proper care, more as demonstration projects than electricity powerhouses. In their defense, they did set a precedent that was put as an example to push for other projects everywhere in the world.

Table 3
Spanish capacity factors over 1999–2008.

Region	Castilla Mancha	Galicia	Castillay Leon	Aragon	Andalucia	Navarra	Co. Valenciana
Capa. (%)	21.7	20.0	18.2	10.9	8.5	6.4	3.9
CF (%)	22.9	26.1	21.8	26.1	24.4	28.5	24.0
Region	**La Rioja**	**Catalunya**	**Asturias**	**Pais Vasco**	**Murcia**	**Canarias**	**Spain**
Capa. (%)	3.0	2.6	1.4	1.3	1.0	1.0	100
CF (%)	26.2	21.1	24.1	30.6	19.6	28.9	24.9

coal lobbies. In all cases, we only read truths but partial ones as the authors systematically ignore or downplay the defects of their preferred technology (or policy options).

No one will deny that such a bias ought to be absent from academic publications. Yet, we cannot fail to observe that academic outlets geared at RES naturally attract the authors themselves supportive of RES, as their writing style clearly indicates.[26] As a consequence, this community has (unconsciously) turned a blind eye to the capacity factor issue. For instance, the basic tenet of this article could have been published five years ago given that a decade of information was already available for Germany, Denmark, Spain and the UK.[27] More importantly, the literature on capacity factors, as summarized in Table 1 above, seem to have been taken at face value when basic knowledge of statistics warns us to handle it carefully.[28] Indeed, it presents a list of best cases given that the authors select promising sites to study the optimal design of wind turbines. When it comes to guessing a realistic value for the very large deployment of WPG (dozens of gigawatts of capacity), one should realize that we are looking at the top of a distribution, so that the average is bound to be lower and even much lower given the large range of capacity factors that can be observed in Europe.

4. Political economy

Our title here refers to the strategic interplay between economic actors such as firms or consumers and the political sphere understood in a loose manner to encompass central, regional and local governments, congress and local legislative institutions as well as the bureaucracy at all levels. We want to underscore that national targets such as those set in the Kyoto protocol are not straightforward to achieve because original objectives get diluted and distorted along the necessary steps to carry them out. We point at two political forces, opposition and support, that end up reducing the efficiency of WPG at country level (in terms of carbon emissions reduction). In our opinion, they make the greatest contribution to the puzzle presented in this paper.

4.1. Political opposition

Given an expected country wide price for WPG,[29] rational investors will always try to sit wind farms at optimum sites, i.e., where capacity factors are greatest. We should thus expect most investment to take place in those coastal areas where wind is strong. That is correct if the full cost is independent of geographical location. Yet, one frequently observes political opposition in those coastal areas that are either densely populated or whose economic activity depends heavily on tourism. This attitude is similar to the political opposition to the sitting of public infrastructures known as "not in my backyard" (NIMBY). Both issues share the same basic characteristic: at country level, few people are visibly hurt while all enjoy the benefits without noticing.

When the erection of a wind farm is thought (may be equivocally) to have adverse effect over the quality of life or the local economic climate, local people logically oppose the project. The positive side is the carbon emission reduction brought about by the projected farm; yet, it is not enough in itself to force the closure of a carbon emitting plant so that we at (country levels) only enjoy a marginal improvement of air quality and the knowledge that carbon emissions are reduced by a few tons, which goes a long way from meeting our country's commitment.

The best sites, from the wind resource point of view, are thus associated with relatively larger cost and delays. Rational investors thus switch their projects from first-best locations to second-best ones, typically in-land. As a consequence, the average capacity factor of the country is far from its maximum; it can even decrease with the large scale deployment of wind power into areas of medium quality. Notice then that plenty of unexploited optimal sites remains available for future development, if the political opposition can be appeased by adequate educative measures and financial incentives.

The development of wind power in Germany illustrates well the trade-off. Enzensberger et al. (2003) reported that until the 3 GW threshold was met (around 1998), wind power development was driven by partnerships (Brgerwindparks) using 70% of debt finance and 30% equity from local residents. By mobilizing a large number of wealthy and influential people, each project was able to efficiently counter local opposition to farm sitting. The success of the formula leads to marketing in the urban areas and the transformation into a full fledged industry that, however, lost its "green roots" origins and thus some of its local political support.[30]

4.2. Political support

It has been observed, in Europe (e.g., Spain and France), that wind farms have been welcomed in rural areas who suffered from emigration toward urban centers in the last decades of de-industrialization. Support comes in the form of red-tape reduction, inexpensive lease of land, tax exemptions, technical service provided in-kind by public agencies, equity participation in projects and help to secure finance from public *loan & saving* institutions.

[26] This avowed bias has been defended as a response to the political clout of the fossil fuel lobbies in order to put RES on a level playing field.

[27] We believe nevertheless that our data gathering helps draw a more complete picture of wind power status in Europe.

[28] Such a cautious approach was certainly not followed by the wind lobby. But yet again, they are not in charge of producing unbiased reports; it is only natural for that lobby to emphasize positive estimation results since, in theory, it is possible to install large amounts of WPG at optimal sites and still reach a high capacity factor.

[29] We use this vague terminology since it can be either a deterministic feed-in tariff or the full price expectation under a quota system.

[30] Incidentally, we note from the commercialization prospectus information reported by Enzensberger et al. (2003) that the (low) capacity factor of German wind farms was correctly assessed by private developers.

Table 4
German capacity factors over 2005–2008.

Lander	Niedersachsen	Brandenburg	Sachsen-Anhalt	Schleswig-Holstein	Nordrhein-Westfalen	Mecklenburg	Rheinland-Pfalz	Sachsen
Capa. (%)	25.2	15.8	12.6	11.3	11.2	6.0	5.0	3.6
CF (%)	19.5	18.5	20.9	21.0	18.0	19.2	17.0	17.4
Lander	Thuringen	Hessen	Baden-Wurttemberg	Bayern	Bremen	Saarland	Hamburg	Germany
Capa. (%)	2.9	2.1	1.8	1.7	0.4	0.3	0.1	100
CF (%)	18.4	15.9	13.4	14.0	21.1	17.8	16.9	19.0

This is a perfectly rational behavior on the part of local authorities, within the general process of political devolution from the central power toward the regions (and counties or provinces). Although RES support schemes are designed at country level, all regions are allowed to participate in the development of RES.[31] Yet, because regional authorities are not bound by any formal commitment regarding carbon emission reduction, they logically pursue more "down-to-earth" objectives such as sustaining employment and economic development. Regional authorities then define potential sites for wind power development and allocate them to private investors in beauty contests where local ties matter. In many instances, the industrialist who will build and exploit the farm is a national firm because local politicians care for the creation of local jobs and the possible local expansion of the industrialist in the region. This is more likely to happen when the firm is a national.

In our opinion, the key to understand the capacity factor puzzle is the role of public funds to finance investor owned wind farms. Although nearly all wind power developers are private for-profit firms, they finance most of their ventures through debt because the entire cost of a wind farm is to be paid up-front while revenues stretch over a 20 year period. Private banks agree with developers that the capacity factor is the decisive criteria to ranks projects[32] and since they require a large profitability, only projects at top sites get their backing. Public *loan & saving* institutions analyze wind farm development from a different point of view because their charters are about sustaining the local economy rather than maximizing profit.[33] A local bank will thus finance any wind power project with a positive NPV because it creates jobs and increases revenue for many local firms during the first years of the project and at the same time, guarantees that future repayments will enable to recover the initial outlays.

Spain appears to be a case in point. Dinica (2008) explains that the ramping up of the first 3 GW of wind power (achieved around 2000) used almost exclusively public private partnerships (PPPs). For the ensuing period, Stenzel and Frenzel (2008) report the pro-active behavior of Spanish utilities who teamed with regional governments and *loan & saving* institutions to develop the capacity allocated by the central government. With the advent of the 2004 law guaranteeing a generous price valid over the lifetime of the investment, calls for wind power development has been covered several times over. At the moment, virtual all Spanish "cajas" are financing wind farms.[34]

Germany and Spain which account for the bulk of wind power in Europe thus partake of the fact that their initial stage of development did not obey a profit maximization rationale but a desire to ramp up a renewable technology for electricity generation. Over the last decade, purely private investors have entered the arena but centralized public institutions (e.g., European Investment Bank, KfW, 2007[35]) or local *loan & saving* institutions (e.g., Hamburg and Schleswig–Holstein bank) are still major financial backers.

Our comparative analysis of the behavior of private and public banks with respect to the financing of wind farms offers a forceful explanation for the large scale deployment of wind power capacity in sub-par regions as we document hereafter.

4.3. *Regional variability*

If the capacity factor was the unique development criteria, then all regions lacking adequate wind sites would see zero development; this is indeed the case for London, Paris, Berlin and Madrid because land there is expensive, wind not so strong and its quality distorted by the presence of buildings. For regions lacking good wind resource, the same roughly applies although the political pressure alluded to before has lead to some development. As the share of installed capacity in those regions remains quite low, their impact on the national CF is limited; hence their low CF contributes little to the overall national achievement.[36] Now, for regions that do possess top sites, we should observe high CFs but at a smaller scale of deployment when compared to the best region in the country since top sites are generally unequally distributed among regions. If deployment obeyed more or less the above principle, regions with the largest share of national capacity installation should also be those with the highest CFs. The following data show that this conclusion fails to hold among the regions of Germany, Spain and the UK (for which we could collect data).

The breakdown of UK capacity factor among its component countries is only available through a BERR short study regarding a sample of wind farms over the 2000–2004 period. Northern Ireland is first with 34.8% (but only eight farms are measured), next is Scotland with 29.4%, then Wales and England with 25.2% both. Although England has the lowest CF, it is the region with the largest share of the UK wind farms.

To ease the reading of Tables 3 and 4 regarding Spain and Germany, Fig. 6 reproduces the maps of regions. German output data for 2007 are taken from a DEWI report which uses potential output. It is thus rescaled using the lower official output for Germany as a whole published by the federal ministry. Spanish

[31] The desire to board the "sustainable development" train of political correctness has probably led many local governments to launch demonstration wind power projects in unfitted areas such as valleys but being small size it is unlikely that they bear upon the country average capacity factor.

[32] In this, they concur with central authorities precisely because support schemes such as feed-in tariff and green quotas are designed to align incentives.

[33] The central government affords them lax refinancing rules and protection against unfriendly acquisition in exchange of carrying out its local economic policy towards small and medium businesses.

[34] Some major players are CajaMadrid, LaCaixa (Catalonia), Caixa Catalunya, or Bancaja (Alicante and Valencia).

[35] For 2007, it reports .5bn€ of loans in the areas of electricity generation, transmission and environmental technology (p. 22) and 3.8bn€, loans at favorable interest rates to promote renewable energies (p. 56).

[36] Likewise, the European average CF is driven by Germany and Spain so that success or failure in small countries weight for little in the overall European score (cf. Table 2).

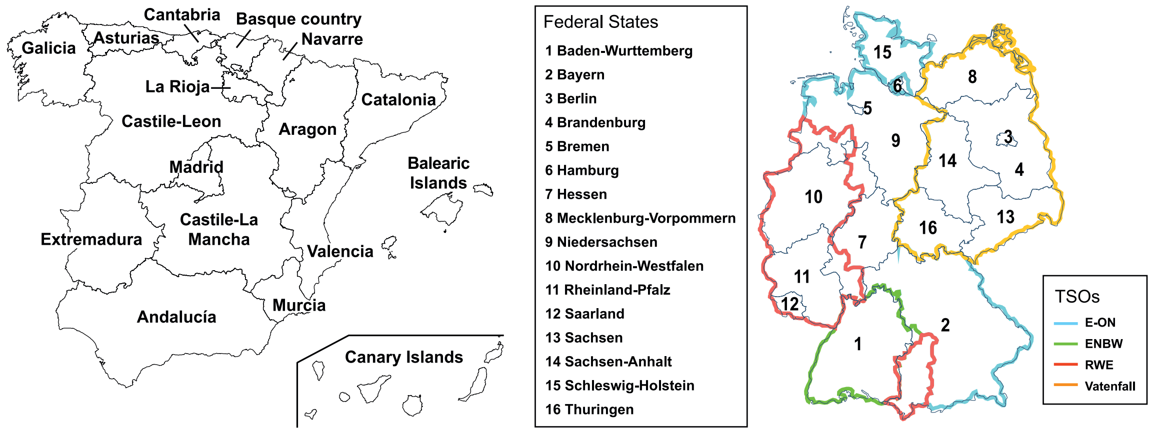

Fig. 6. Spanish autonomous communities & German Landers.

data use yearly reports from REE and CNE (some region have less than a decade of data).

The previous tables show that there is a lot of development in the most windy regions but also that intensive development takes place in sub-par regions. Given that investment projects at the best sites have failed to materialize (or are unduly slowed), it might be useful and politically acceptable to introduce positive discrimination measures for sitting wind farms at the best sites. Public authorities could try to improve media communication and adopt counter-vailing incentives such as co-sharing the benefits of WPG to diffuse local political opposition. More regional statistics about capacity factors would obviously need to be gathered to guide such a change in policy.

National support schemes have been, up to now, formally insensitive to geography as a consequence of non-discriminatory rules for public funds spending. There is, however, an indirect location sensitivity in Germany, Netherlands, Portugal, Denmark and France because payments can decrease with the achieved CF (cf. Klein et al., 2008, p. 28). The most relevant case is Germany. Since 2000, a wind farm receives a full tariff for 5 years after which its CF is assessed. If found below 23%, it is eligible for a further 15 years at the same tariff whereas if found above 42%, the reduced tariff kicks in; lastly, a linear formula applies in between.[37] In France, full payment lasts a minimum of 10 years and is extended another 5 years if the CF is below 27% and reduced to a third if the CF is over 41%. In both countries, the average CF falls below the minimum threshold, hence the immense majority of wind farms must be getting a flat rate over their lifetime (these complex formula seems to apply at the margin only).

5. Conclusion

The capacity factor of wind power is a crucial information for both private and public decision makers and the reliance on the popular 35% value is not without consequences. The contrast with the realized capacity factor of 21% (on average for the last five years) means that the levelized cost of WPG is raised by $\frac{35}{21} - 1 \simeq 66\%$ above the standard estimate (whatever that may be). This is without much consequence for wind farm developers as their careful studies enable them to anticipate the CF of their projects with great precision and carry on only if the NPV is positive. The main consequence of the cost increase we uncovered is seen at the macroeconomic level. That WPG has been a success in many countries is proof that the feed-in tariffs have been adequately set above levelized cost to motivate entry. Meanwhile total capacity is small, paying a high price for energy has virtually no impact over the consumer's bill. Yet, once wind power starts to account for a significant share of electrical output, governments become eager to scale down their schemes before they become too costly. Insofar natural gas and coal prices remain at their average over the last decade, wind power, on average in Europe, is not competitive and must then remain supported explicitly.

The fact that WPG happens to be less efficient than previously thought is no reason for society to withdraw its support since WPG remains the unique RES able to expand on a large scale at a reasonable cost to meet committed RES targets (and carbon emission reduction).[38] Moreover, new technologies such as solar thermal, solar photovoltaic, tidal, wave power or even fuel cells in conjunction with the formers are emerging and may someday become as competitive as WPG to meet our environmental goals. Tracking the progress (or lack thereof) in each field for institutional support is thus essential to avoid policy being trapped into a sub-optimal renewable technology.

A more direct policy implication of our findings regards the national character of current support schemes. The *value for money* of taxes[39] channeled toward WPG support schemes currently differs. Somehow exaggerating, one Irish Euro produces twice as much carbon saving as one German Euro. If schemes were not compartmented by local financing and allocation schemes, arbitrage would occur and guarantee an optimal employment of European public money in WPG. Beyond state aid in disguise[40] and transmission congestion, it is hard to imagine an objective reason to impede German public funds from being used to develop WPG projects abroad with the resulting

[37] We use BWE's (2004) example computation for the reference yield of $\frac{4.9\ \text{Twh}}{8760 \times 2\ \text{MW}} \simeq 28\%$ so that the maximum 150% threshold gives a 42% CF (cf. FGW for the official computations). To extend the full payment for another maximum 15 years, one needs 90 two month extensions, hence $90 \times .75 = 67.5$ percentage points below the 150% threshold, i.e., a yield at 82.5% of the reference, i.e., a 23% CF. As of 2009, full tariff is 92 €/MWh while reduced tariff is 50 €/MWh. The law also eliminates second stage payments for installations falling below 60% of reference yield (about 13% CF). This is supposed to guarantee minimum yield but looks difficult to implement in practice.

[38] The levelized cost of wind power is on average in Europe around 70 €/MWh while that of solar photovoltaic power is still above 200 €/MWh.

[39] A levy applied upon electricity prices to finance a support scheme is a tax. Likewise a renewable obligation artificially raise producers' cost and is also akin to taxation. The only difference lies in their determination, the former being exogenous and the latter endogenous.

[40] Recall that the payments to wind farms located in rural areas come from the electricity bill of city-dwellers.

"green" electricity being entirely bought by German customers.[41] European citizens concerned by climate change, and to a lesser extent taxpayers, deserve a greater effort from energy policy makers to improve on this issue.

Finally, it is worthwhile commenting on the notable difference between the present average EU CF at 21% and the US one at 26%. Firstly, the US is a larger territory with the opportunity to utilize sites with better wind resources so that in practice, valuable sites are probably twice as numerous compared to Europe. Secondly, population density is overall less in the US (31 vs. 112 people per km^2) and more concentrated to low wind-speed regions so that the most productive sites do not offer political resistance to development. Lastly, financing seems to be predominantly private in the US and thus obeys more strongly the CF criteria.

Within Europe we can make a similar comparison of the UK vs. the continent. Whereas the former possesses an objectively better wind resource, it has of yet failed to develop it at the speed of continental countries such as Germany or Spain. The continental use of direct subsidies (feed-in tariffs) and reliance on public finance may have led to an inefficient development but it was a rapid one. It may thus be optimal to decentralize the development of renewables toward local actors with a lax enforcement of efficiency criteria (e.g., capacity factor) or construction rules in order to enable a rapid take-off but at the same time, the central government should commit from the start to tight enforcement rules for the second generation to avoid being trapped into the "subsidies for ever" spiral by making clear what is the overarching objective of the entire policy. The remaining difficulty is obviously to specify what defines the jump from first to second generation of a given renewable technology.

6. Uncited reference

Johansson and Williams (1993)

Acknowledgments

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[41] Notice that the local health benefits of carbon emission reduction would still take place in Germany since German thermal generation would be substituted by green foreign electricity.

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