

Capacity Factor of Wind Power

Realized Values vs. Estimates

Nicolas Boccard*

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Abstract

For two decades, the capacity factor of wind power measuring the mean energy delivered by wind turbines has been assumed at 35% of the name plate capacity. Yet, the mean realized value for Europe over the last five years is closer to 21% thus making levelized cost 66% higher than previously thought. We document this discrepancy and offer rationalizations, emphasizing the long term variations of wind speeds. We conclude with the consequences of the capacity factor miscalculation and some policy recommendations.

Keywords: Electricity, Renewables, Planning

JEL codes : L51, H42, D61

1 Capacity Factors Puzzle

Wind Powered Generation (WPG) is the top player in the renewables field and can only benefit from more information regarding some of its characteristics. Very little has been published regarding capacity factors at the global level of an entire country. Contrary to the implicit popular opinion, the wedge with local values happens to be large because particular findings cannot be generalized. Our aim in this section is to contrast capacity factor estimates from the academic literature with the actual level computed from recorded installation and production in Europe.

1.1 Theory and Local observations

The *capacity factor* (CF) of wind power is the ratio of average delivered power to theoretical maximum power. It can be computed for a single turbine, a wind farm consisting of dozens of turbines or an entire country consisting of hundreds of farms. Although geographical location determines in great part the capacity factor of a wind farm, it is also a matter of turbine design. Indeed, a large rotor combined with a small generator will take advantage of just about any wind and achieve an artificially high CF, obviously at the cost of a low yearly energy output. Most of the literature on capacity factors is in fact composed of studies trying to identify optimal turbine designs for particular places; the reported CF is then the one corresponding to maximum yearly energy output.

* Departament d'Economia, Universitat de Girona, 17071 Girona, Spain. Financial support from Instituto de Estudios Fiscales, Generalitat de Catalunya (contract 2005SGR213 and Xarxa de referència d'R+D+I en Economia i Polítiques Públiques) and Ministerio de Educación y Ciencia (project SEJ2007-60671) are gratefully acknowledged.

Table 1 displays a number of capacity factor estimates, mostly obtained with computational models using wind speed data (and sometimes of wind power output at specific farms).¹ 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 global wind power resources are based on more realistic values: [Grubb and Meyer \(1993\)](#), [World Energy Council \(1994\)](#) and [Hoogwijk et al. \(2004\)](#) use respectively 22.5%, 25, 1% and 26,5%.²

• 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. (2004) : 31%, L, MD, US	• 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

Letter codes are G for global, L for local, T for theory and [ISO 3166](#) country codes

Table 1: Capacity Factors Estimates

1.2 Global realizations

Table 2 contrasts the theory with actual records of WPG in European countries ordered by currently installed capacity. Our main reference is the *wind energy barometer* of think-tank [EurObserv'ER](#) with some corrections from more reliable sources whenever available.³ We also use the mid-year average installed capacity to mitigate for the continuous development of WPG; it thus yield greater capacity factors than the mere ratio of output to capacity for a given year. Although the capacity (GW) and output (TWh) figures reported here have been published every year over the last decade by national public agencies, they have seldom been used to produce a capacity factor ratio, let alone a country comparison.

The average European CF over the last five years is less than 21%, significantly lower than the 24% claim made by the European wind power lobby for a “normal wind year” at the current level of development (cf. [EWEA \(2008\)](#) p29). Realized capacity factors oscillate across time and across regions

¹We searched the Elsevier, Wiley and Springer databases for “capacity factor” AND “wind power”.

²We convert their full-load hours assumption into CFs.

³While there are only minor revisions regarding installed capacity from year to year in all sources, generation data show important discrepancies, both between year to year reports of the same source and between different sources. We have favored the most recent reports and those of Transmission System Operators over European think tanks. For the UK, we use [BERR \(2008\)](#); for Spain, reports from the TSO [REE](#); for France, the report by [France Energie Eolienne](#).

Area	EU15	DE	ES	DK	IT	UK	FR	PT
Capacity (GW)	56.3	22.2	14.1	3.1	2.7	2.5	2.4	2.2
Energy (TWh)	97.7	33.7	28.8	6.1	4.2	5.3	4.2	3.8
Capacity Factor (%)	20.8	17.5	24.8	22.8	19.1	26.1	22.3	22.7

Area	NL	AT	GR	IR	SE	BE	PO	CA	US
Capacity (GW)	1.7	1.0	0.9	0.8	0.7	0.3	0.3	2.4	16.6
Energy (TWh)	3.5	2.0	1.9	1.9	1.2	0.5	0.5	4.4	32.1
Capacity Factor (%)	21.5	20.1	29.3	29.3	21.7	20.0	25.9	22.3	25.5

Table 2: Average Capacity Factors over 2003-07

in the 20–30% range.⁴ The higher end is found in Greece, Ireland and UK which benefit from numerous windy coastal areas with low density of population that enable effective siting in those preferable zones. For reference, Table 2 includes the US⁵ and California (CA), the state with the longest experience in WPG; there is a stark contrast with AWEA (2005)’s claim that a 35% capacity factor is typical for the US.

The strongest discrepancy between theory and reality regards the large scale development of WPG with offshore participation. Wild claims are made regarding future possibilities at the 2020-2030 horizons that up to now, in our opinion, are all but warranted by facts. Academic reports regarding the UK by SDC (2005), Gross et al. (2006) or Sinden (2007) borrow at face value 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. The first statement is true but only in relative terms. Indeed, Table 2 indicates that UK WPG outperforms the EU mean by 25% but since the later is appallingly low, the feat is not so impressive. Secondly, given the 27.5% long-term CF average for current on-shore capacity in the UK, future off-shore wind power would need to reach a 43% CF which is quite off the mark at the moment since the 2003-07 average is a meager 26.5%, as one can check from table 7.4 in BERR (2008). The more recent opinion by BWEA (2006) (cf. Table 1 p16) shows more restraint in anticipating capacity factors of 30% for onshore and 35% for offshore.

At the European level, EWEA (2008) assumes that by 2020 capacity factors will reach 29.6% for onshore and 44.6% for offshore.⁶ For onshore, this means that repowering, better siting and improved design of wind turbines would succeed to increase overall efficiency by $\frac{29.6}{20.8} - 1 \approx 42\%$. Summing-up, capacity factors above 30% for onshore and above 40% for offshore appears to be mere leaps of faith lacking the support of either hard data or a proper model of the learning curve able to deliver the promised enhancements w.r.t. currently observed levels.

1.3 Correction for 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 are thus likely to evolve and do not reflect the long term potential of a region. For that reason, a low observed capacity factor may be due to unusually low winds, below their long term potential. Several research institutes from

⁴We only report on areas where wind power is not anecdotal (i.e., makes more than one percent of system capacity).

⁵ The Energy Information Administration (EIA) uses sampled (40%) and estimated (60%) data. As the 2006 CF appear to be an outlier when computed with our usual method, we use the detailed plants file to reconstruct a more sensible value. In any case, some plants reports are highly suspicious so that the overall CFs for the US should be handle with care.

⁶We compute the ratio of expected TWh output per expected GW capacity p30 i.e., $\frac{467}{180 \times 8.76}$ and $\frac{469}{120 \times 8.76}$.

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,⁷ [EMD](#) for Denmark,⁸ [Garrad Hassan](#) for the UK,⁹ [WSH](#) for the [Netherlands](#) and [Elforsk](#) for Sweden). The longest and most detailed range of data comes from Denmark as illustrated on Figure 1.

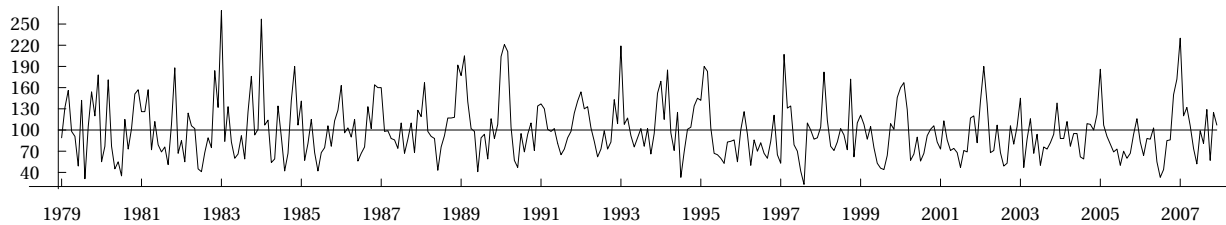


Figure 1: Danish monthly Wind index

Although monthly values differ among countries, one can see on Figure 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 Germany and from 20.9% to 21.9% for the Netherlands. Applying the Danish index which is the longest and most reliable to the EU-15 data over the 2003-2007 period would increase 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 output measure that amounts to an implicit wind index which is, on average over the last 15 years, at 20% below the wind index computed by [ISET](#).

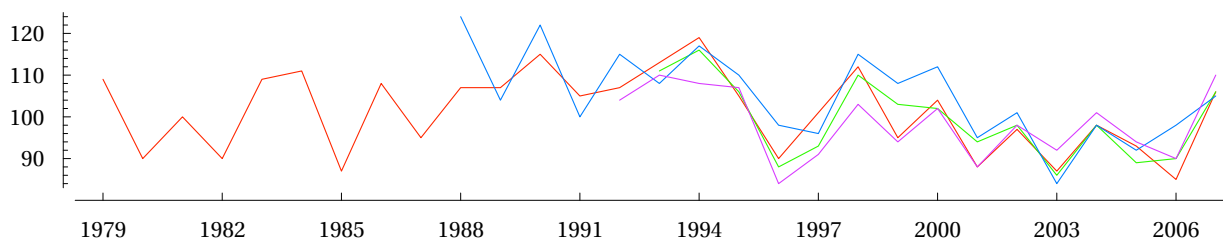


Figure 2: Northern Europe Wind indexes

2 Rationalization

In this section, we offer several avenues to rationalize the wedge between the theory and practice of capacity factors: *shadowing*, *learning curve*, long term evolution of wind patterns, *NIMBY* and *selection bias*.

⁷The denominator for the index is the average WPG output computed from wind speed series at five locations over the 1950-2000 period.

⁸As explained in [Nielsen \(2004\)](#), the 1976-78 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.

⁹Same as Denmark using the 10 year average previous to the year being computed.

2.1 Shadowing

A first technical answer to the capacity factor puzzle is *shadowing*, a physical phenomenon that originates in 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. As reported by [Kaltschmitt et al. \(2007\)](#) p331, the output of a wind farm is on average 92% of its nameplate capacity i.e., although a single 2MW turbine can yield 2MW under a large span of good wind speeds, a farm of 50 units will never yield the nameplate capacity of 100MW but 92MW at most. Taking into account shadowing raises the European capacity factor to 23% instead of 21%(i.e., a 10% compensation).

2.2 Learning Curve

The next piece of explanation is an over-optimistic *learning curve* effect. Up until the last decade, California was the only place publicizing aggregate information regarding its wind power program. The [Energy Commission](#) reports that the state capacity factor grew from 13% in 1985 to 24% in 2001 (cf. [California Energy Commission \(2001\)](#) p.15). This is obviously due to technological progress in wind turbines design and possibly to better siting. This hard fact is proof that the learning curve was at work for WPG during the 80s and 90s. Over the last decade, the wind power industry has noticed an even stronger development. It may have lead some to believe that the aggregate CF would keep rising towards its theoretical limit, which is the CF of the best site in the territory. This did not happen because averages usually do not converge to the maximum of the sample. The California CF, for example, decreased since 2001.

2.3 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. By extending the study to the 1979-2007 period, we can confirm this judgement. Figure 3 displays the 10 years moving average of the Danish Wind index (bold curve) together with the NAO index.

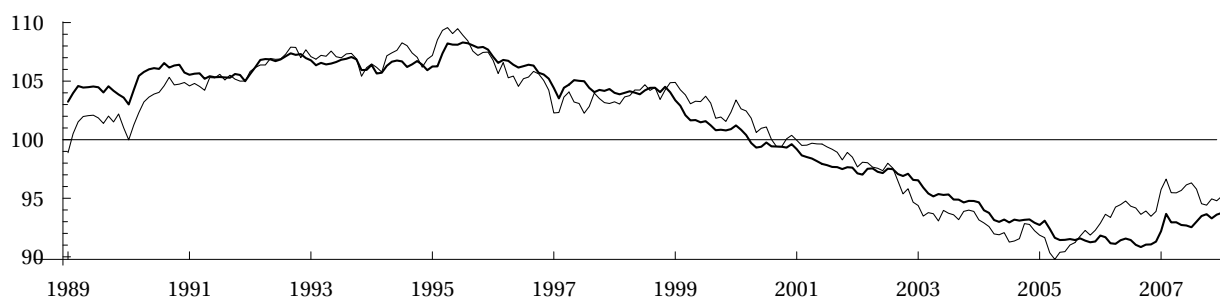


Figure 3: NAO index vs. Danish Wind index

To produce Figure 3, we first scale the monthly NAO series by a factor 1000. Over 3 centuries, the NAO mean is $\mu = 31$ while its coefficient of variation is $\gamma = \frac{\sigma}{\mu} = 48\%$; 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 Danish wind indexes is $r = .49$, reaching $\hat{r} = .96$ for the 10 years moving average. A least-squares fit of the Danish index over the NAO one (intercept 96, slope .0288) is used to rescale the NAO index for the join plot on Figure 3.

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 with the top panel of Figure 4 displaying the 10 years moving average of the NAO index over three centuries.¹⁰ One clearly sees a rise 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. The bottom panel, by concentrating on the last four decades, warrants this opinion. We see how the one year moving average, displayed in grey, varies widely during the year, 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.

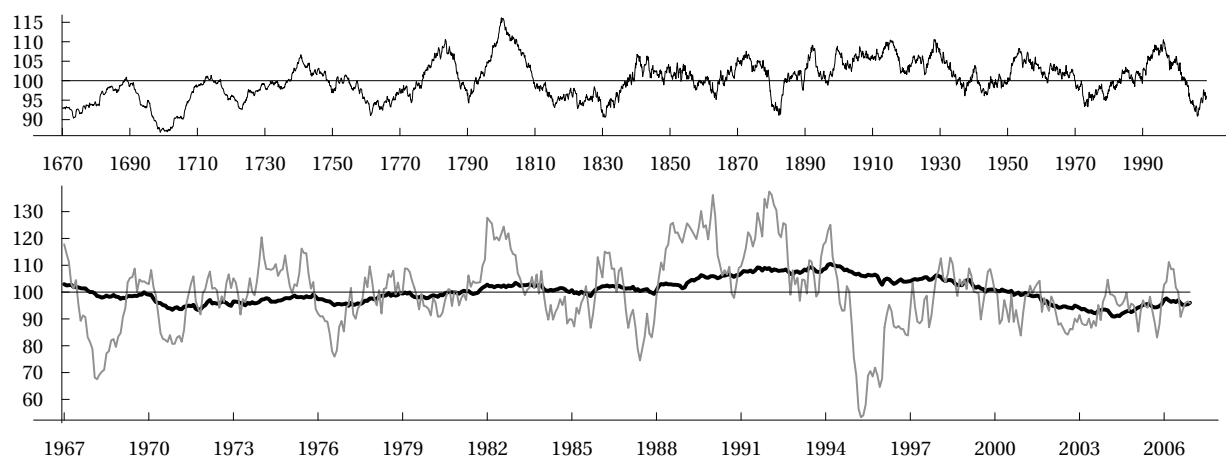


Figure 4: Long Term Change in the NAO index

2.4 NIMBY

Given non-discriminatory WPG subsidies, a rational investor will always try to sit a wind farm at an optimum site, so that we would expect most investment to take place in those coastal areas where wind is strong. That is correct if the full cost is location independent. Yet, one frequently observes **NIMBY** opposition in those coastal areas that are either densely populated or whose economic activity depends heavily on tourism. On the contrary, deserted rural areas greatly benefit from the siting of wind farm in terms of job creation so that local authorities adopt the reverse attitude. The best sites, from the wind resource point of view, are thus associated with relatively larger cost and delays; this leads investors to develop in-land at subpar locations. As a consequence, the average country CF is far from its maximum; it can even decrease with the expansion of wind power capacity into areas with medium quality wind resource. There remains however plenty of unexploited optimal sites for the future if the NIMBY syndrome can be appeased.

2.5 Selection Bias

¹⁰We 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 one percent above long term average.

Our last and most controversial rendition of the mismatch between theory and practice of capacity factor is the *selection bias*. Firstly, academic outlets geared at renewables naturally attract supportive authors, as their writing style indicates. This avowed bias may lead them to understate unpromising results (and overstress those favoring the advent of renewables). Secondly, and more importantly, Table 1 is a list of best cases. Indeed, it would not make sense to study wind speed data at a location where nobody will ever build a wind farm; the selected sites are thus necessarily the most promising ones for WPG. Given that we are looking at the top of the distribution, it is no surprise then that capacity factors recorded over entire territories end up being much smaller than the aforementioned estimates.

A related phenomenon is the emphasis of the wind lobby on capacity installation with the associated neglect of energy output and capacity factor.¹¹ This is a rational behavior because wind turbines and farms (capacity) are the visible side of WPG that has to be “sold” to the public to guarantee continued political support and subsidies (or renewables obligations). Public authorities may even follow the same path since they have an interest in altering the fuel mix towards renewables, in order to meet Kyoto targets and reduce dependence on imports. Yet, as we argue in the conclusion, the capacity factor matters for future policy making.

3 Conclusion

The capacity factor is a crucial information for decision makers and the reliance on the now popular 35% value is not without consequences. For the private investor, the net present return of a wind turbine is proportional to its average CF over the 20 years lifetime of the equipment. At the EU level, a realized capacity factor of 21% means that the average levelized cost of WPG is raised by two thirds. Indeed, average cost is the ratio of fixed cost to capacity factor, up to a constant (8760, the number of hours in a year). Since the ratio of predicted to real CF is $\frac{35}{21} \approx 1.66$, real cost is 66% above the standard estimate.

The wedge between anticipated and realized CF implies that some private investors may have been victims of a variant of the winner’s curse, the discovery after sitting the turbine that the location is not among the best. If one insists on treating investors as rational then it must be the case that realized capacity factors are still large enough to make projects profitable given the subsidies guaranteed by national regulatory regimes and local political support.¹² As we show in [Boccard \(2008\)](#), this prediction seem confirmed for most of European regions with the possible exception of South-Western Germany. As for the future, the knowledge that the average capacity factor is lower than expected may slow the overall development of WPG since the projects in the least promising sites may not be carried out. The bright side of the picture is that investment will concentrate on the most windy areas and become more efficient.

The novel information on wind power provided in this note is of greatest importance for public authorities because the capacity factor at country level exactly determines how much carbon emissions are avoided in the electricity sector. Beyond this environmental objective, WPG also participates in reducing the dependence on fossil fuel imports (traditionally used for the production of electricity). The fact that WPG happens to be less efficient than previously thought is no reason to withdraw

¹¹The capacity unit MW is present dozens of times in the [EWEA \(2007\)](#) or [GWEC \(2007\)](#) but the energy units MWh or GWh are nowhere to be found.

¹²Beyond helping with red-tape, local support can take the form of inexpensive lease of land, access to cheap borrowing from savings & loans institutions, tax exemptions or technical service provided in-kind by public agencies.

support since it remains the unique RES able to expand on a large scale at a reasonable cost to tackle the EU's Kyoto commitment (and beyond). Yet, new technologies such as solar, tidal or fuel cells are emerging and may someday become as competitive as WPG to meet our environmental goals. Tracking the progress (or lack thereof) in each field is thus essential to avoid been trapped someday 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 taxes¹³ channeled towards 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, arbitrage would occur and guarantee an optimal employment of European public money in WPG. Beyond state aid in disguise 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 green electricity being entirely bought by German customers.¹⁴ 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.

Lastly, national support schemes have been, up to now, quite insensitive to geography as a consequence of non-discriminatory rules for public funds spending. Given that investment projects at the best sites (with the highest CFs) often fail to turn to reality, it may be time to introduce a dose of positive discrimination. Public authorities should try to improve media communication and adopt counter-vailing incentives such as co-sharing the benefits of WPG to diffuse local political opposition (NIMBY). More regional statistics about CFs would obviously need to be gathered to guide such a policy.

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¹³A 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.

¹⁴Notice 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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