WIND POWER HAS A CAPACITY CREDIT
A CATALOGUE OF 50+ SUPPORTING STUDIES

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Abstract

The capacity credit of wind power in a grid has received quite some attention in the past. In the early days of wind power, the capacity credit, or rather the perceived lack thereof, was a grave concern for the large-scale development of wind power on a nation-wide basis. Therefore, a number of studies was made since the 1970ies, arriving at the conclusion that a) wind power has a capacity credit, and b) the capacity credit is around the mean wind power output for small penetrations of wind power in the grid, and drops to a value near the minimum wind power generation for larger penetrations.

This paper describes some different approaches to the capacity credit of wind energy, and provides links to a large number of studies, predominantly for European countries and from the earlier years of the development. Nowadays, the capacity credit is often just a sub-topic for the larger studies on how to integrate renewables, especially intermittent renewables, in the system. The sole aim of this paper is to provide a data base of most of the available literature to the topic, and to end the discussion *whether* wind power has a capacity credit: all studies from research institutes, consultants and the power industry itself show that it has one.

1 Introduction

A few years ago, the whole concept of a capacity credit (CC) of wind energy was declared dead. This was based on the notion that the liberalised markets would figure out themselves how to treat additions to the power plant mix [1, 2]. Since a single wind power plant was not thought to have any capacity credit anyway, its assessment would be subsumised under the more general assessment of the market demand for power from the new plant. Nabe [3] also dismissed the notion of the capacity credit as insufficient to assess the value of wind energy in the liberalised markets. On the other hand, he proposed a system where the capacity credit is used as a yardstick for further renewable expansion, giving green certificates tied to the capacity credit of the plant.

The lack of a firm capacity of a single wind farm is also still regularly quoted in the press as one of the major arguments against wind power. This refers to letters to the editor in the Frankfurter Allgemeine Zeitung and other general media over the last few years. Every other time the topic of wind energy is in the news, someone will write in and claim that it is an unreliable resource, and to account for the unreliability there has to be the same amount of spinning reserve in the grid. This spinning reserve would then have to be taken as the ecological and economical backpack of wind energy. In the proper terminology, those statements negate the capacity credit of wind power.

The capacity credit concept had its heyday in the seventies and eighties, when a lot of different studies were performed in various countries. One of the largest such studies was the EU funded Wind Power Penetration Study, which was done for all (then 12) EU countries. In recent years, no new dedicated studies to the capacity credit of wind energy have appeared, although the concept (named explicitly CC or not) has been used in recent studies on the integration of wind power into the grid.

However, accounts of the death of the capacity credit concept seem exaggerated. Recently, the US PJM Interconnection reliability area (Pennsylvania, New Jersey and Maryland) has acknowledged the capacity credit of wind power [4], applying a three-year rolling average of the wind project's actual performance during PJM's peak hours. Before this measurement becomes available, PJM uses a "class average" of 20% of the nameplate capacity. This credit can amount to nearly 1 USc/kWh.

This new development makes a look at older results relevant. This paper tries to give a thorough overview over the earlier and recent literature to the topic, leaving an in-depth analysis of the information collected for a later time. Since the smoothing out of variations in the wind power when collected over a large area is related to the CC, an extra chapter tries to collect the information on that point, too.

2 The Concept

In the literature, the capacity effects of wind power are not always well defined. There is a jumble of capacity factor, capacity credit, displaced capacity and other ideas. Milligan [5] gives a good overview of some algorithms.

The easier one to assess of the capacity effects of wind energy in the grid is the **firm capacity**. This is the fraction of installed wind capacity that either is online at all times or with a probability similar to the availability of a fossil fuel power plant. Fossil fuel plant availabilities seem to have large scatter in the literature. The CEGB used 79-92% [19], while Bernow *et al* used 84 % [16], quoting the US national average for the forced outage rate as 12.4 % and the maintenance outage rate as 13.6 %. The firm capacity might also be expressed as an absolute value, but similarly to the LF, the fraction is usually more meaningful. This value can be assessed comparatively easily from pure wind data - in fact, for all of Europe this has been tried by Landberg [6]. According to his paper, wind turbines will only in 2 % of all cases not produce power anywhere in Europe.

Load Factor (also known as **Capacity Factor**) is the percentage of power production as a fraction of the nameplate capacity of the wind energy conversion system. This can be the instantaneous value, but often will be the yearly mean. The latter can also be expressed as **Full Load Hours** via a multiplication with 8760. Typical values are 20-30 %, or 1500-3000 full load hours, respectively.

Penetration is the percentage of wind power in the grid. This is usually defined as the amount of wind energy delivered during a year, compared to the total electrical demand during that year. Additionally, sometimes an instantaneous penetration is used, being the current (10-min or one-hour) penetration. This has reached over 100% in some grids (western Denmark, Schleswig-Holstein, some areas of Spain). However, it is also seen used as installation penetration, meaning the percentage of installed wind power megawatts in the totally installed power system. To confuse matters even more, some studies also use additionally installed megawatts of wind power, and scale this as a percentage of the pre-existing power plant mix. Luckily, this is quickly transformed into an installation penetration, but no quick rule of thumb exists for transforming that into a proper demand penetration.

Loss Of Load Probability (LOLP) is the probability that a **Loss Of Load Event** (LOLE) occurs. Typically, system operators aim for 1 event in 10 years (or better, of course). For the LOLP, the match between resource and demand is decisive, as well as the response times of the existing power plants. Power supply systems with a high percentage of storage (*eg* pump storage) can accommodate higher penetrations of wind energy than supply systems consisting solely of nuclear and coal fired plants.

Finally, the **Capacity Credit** (CC) assigned to a regenerative conversion plant is the fraction of installed (regenerative) capacity by which the conventional power generation capacity can be reduced without affecting the loss of load probability [7, 8].

A proper capacity credit assessment can therefore only be made through a full modelling of the power system, preferably on a hour-by-hour basis and stochastically including the probabilities for each power plant to drop out. This is quite an effort, and can usually only be done by the utilities themselves, or by research groups close enough to them to have access to the power grid data. However, Milligan and Parsons [9] proposed a short cut, where the full analysis is not possible, using the relative wind power production at the (up to 30% of) hours of the highest demand. Milligan [10] also investigated whether a single year and a simulation technique is sufficient to capture the variations in capacity credit in a 13-year set, and found that it is not enough, even though the simulation technique tried out for one site in North Dakota worked reasonably well.

One note should be inserted here on the relevance of the capacity credit considerations in the liberalised market. The capacity credit is most relevant for the discussion in the classical vertically integrated utility world, where everything related to electricity was in one hand, and the generation system, transmission system and distribution network could be planned with long lead times. This explains the lack of attention the topic has received in recent years. Since the liberalisation of the markets and the unbundling of Transmission System Operator (TSO) responsible for the stability of the system from the (many) power generation companies, the situation has become more complex. The idea behind the liberalised market is to force competition in the electricity system, thereby reducing prices for the consumer, while letting the TSO handle the stability of the grid. In this system, the market rules are more important than in the old setup, and overly zealous market rules can work against system stability. In the case of California 2000, e.g., forcing all electricity to go through the short-term markets without price-stabilising long-term contracts amounted to a “license to steal” [11] for the incumbent large-scale generators, despite the fact that on paper enough generation capacity was available. Also in Europe the market price for electricity is artificially low due to the still existing overcapacity of written-off power plants, which makes it not economic to invest in new power plants, except for incumbent large power companies which can take a similar capacity out of the market. Having said all this, the capacity credit still goes into the long-term adequacy considerations for the power system, be it market-based or liberalised.

3 Previous Capacity Credit Assessments

3.1 The CC in large grids

Even from the early stages of development the capacity credit of wind energy has received attention by researchers. A short overview over early results can be found in Diesendorf *et al* [12]. Let me quote a few main points also found in other publications: for small contributions of wind energy (<5 % of total demand), wind energy's capacity credit is roughly equal to the average wind power. At large penetrations (>40 % generation), the capacity credit tends towards a constant value determined by the loss-of-load probability without wind energy and the probability of zero wind power. A grid composed of few large power plants attributes a higher capacity credit to wind than one composed of many small units. Dispersion of wind power can raise the capacity credit about 20% over its value for just one site. A good correlation between wind power and demand can lift the capacity credit by about 20%. Even though these results were derived with relatively simple tools, and though the actual numbers will most likely depend on a number of factors pertaining to the local circumstances, most of the results are still valid.

Selzer [13] showed that Europe's electricity needs could be met with wind energy a few times over. However, the integration into the grid set technical limits for the possible penetration due to the fixed regime of nuclear and cogeneration plant: at high wind energy generation and low demand, some of the wind energy has to be discarded, if not enough storage capacity is available. Based on four national studies, he estimated that the available storage capacity facilitates 10-20 % of the demand covered by wind energy. As well, with the proper operational strategies for the conventional power plants, the rate of acceptance could rise from 8% of peak demand to up to 30 %.

One early study, which already tackled most of the themes in this paper in a well-laid out and thorough fashion, is the dissertation of Robert Steinberger-Willms [14]. He looked at an energy supply from solar energy, including solar power from solar thermal power plants in northern Africa transported via HVDC. For the wind part he worked with just 5 hourly time series from northern Germany. He could show that even with just the 5 time series together, the frequency spectrum was nearly one order of magnitude lower than for just one park at frequencies of 1/6h. This means that the spatial averaging especially takes out the short-time variations in the resulting time series. He could show that due to the stochastic nature of the wind generation (on a time scale comparable with the load variations, that is, intraday), high penetrations of wind power replace base load plant, while the good match between peak load and peak generation has solar power replacing predominantly peak load plant. The available energy storage does not need to be large to be of great benefit for a renewable generation system: even 3 hours worth of storage[i] allow renewable energy to replace much more conventionally generated electricity than without, and the additional benefits already trail off significantly at 12 hours. However, this is calculated for renewable penetrations of up to 1, using 10 times as much energy from solar than from wind power[ii]. The surplus energy from renewable generators was highly dependent on the amount of base load plant. At high penetrations, much energy had to be discarded when 25 % of the power plant mix was base load running on a fixed regime; this lead to the conclusion that high penetrations of renewables demanded a reoptimisation of the existing conventional power plant mix.

In a study for the Cape Cod service area, Johanson and Goldenblatt [15] concluded that it is necessary to utilise hourly wind and load data to establish the value of wind power to the utility. The monetary value to the utility of each added turbine is less than the last turbine, since every turbine replaces power plant further down in the merit order, *ie* the replaced plant has lower fuel cost than the one replaced before that. This is a quite interesting point for the economic assessment of wind power: for a given price of turbine, there is an optimum penetration of wind power in the existing grid. Reoptimizing the plant mix after the inclusion of wind power, more peaking and less base plant was found to be optimal in comparison to the case without wind power. When comparing this mode to a pure fuel saver mode, where the conventional plant still runs as spinning reserve, a larger capacity credit can be achieved, and more money is saved by the utility on fuel and investment. However, for rather small penetration the difference in value for the utility of the two modes was negligible, and only after installing a wind power capacity of 5% of the peak load, did the reoptimisation step yield higher savings.

Bernow *et al* [16] used the ELFIN model for the case of a small utility in the mid-west US, and again found the capacity credit to decrease with penetration. The percentage figures for penetration were scaled by the peak load. They explicitly analysed the benefits of adding another site for diversity of the resource. While for just one good site the capacity credit decreased from up to 100 % for nearly zero penetration to 40 % at 20 % penetration, adding another site decreased the initial capacity credit to between 60 and 80 %, but kept it above the single site CC with 45-60 % at 20 % penetration.

One of the largest studies of the potential benefits in all national electricity grids in Europe was the Wind Power Penetration Study sponsored by the EU Commission. During this study, the capacity credit was assessed for each of the then 12 EU member states.

In the Irish study [17], the capacity credit was assessed with a LOLE method for one single farm and for a collection of farms separately. The capacity credit for the single farm saturated at about 200 MW of wind generators installed (in a grid consisting of 3800 MW generation capability), while for the collection of sites the reduced variability allowed capacity credit increases up to about 350 MW. Again, the relative capacity credit dropped from over 30 % for both options (slightly higher with the one farm for very low penetration) to 9 % (collection) and 5 % (single site) at 4000 MW installed wind power. An early study on wind energy in Ireland [18] concluded that the high contribution of base load plant in the grid of the ESB (43 %) lead to a high proportion of wasted wind energy, since the fixed regime of the base load plant had already all the demand covered. A wind energy installation generating 15 % of the total demand would waste 50 %. Reducing the amount of base load plant, the losses were greatly reduced (ca 10 % at the same level of installation when using only 20 % base load plant). Another conclusion was that smaller generators for the same rotor size could lead to a greater rejection of available power as penetration increases, since the load factor of the turbines increases. For a percentage of 5 % of the total demand covered by wind energy, they found a capacity factor of 52 % of the installed wind capacity for turbines having rated/mean wind speed ratios of 1.5, while for the more typical case of 2 they still had a capacity credit of 24 %. This dropped to 21 and 7 %, respectively, for 35 % of demand covered. From a load duration curve approach they found that the demand

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[i] Read: a storage system being able to cover the average demand for three hours.

[ii] This was modelled after the resource available in Germany. A penetration of 1 means a system completely running on wind and solar energy.

for peaking plant (gas turbines) would rise by 92 %, while the need for base plant would decline by 39 % (at 35 % demand covered by wind).

For the CEGB system (England and Wales) [19], penetrations of 2, 5, 10 and 15 % of wind energy netted capacity credits of 31, 25.6, 19.4 and 15.6 % of the installed capacity. However, these numbers are not quite comparable with each other, since for a penetration up to 5 % all installed capacity was thought to be erected on land with a capacity factor of 34 %, while from that point on wind energy capacity was being built off-shore, with an accordingly higher load factor of 44.8 %. Hence, for very small penetrations the capacity credit reached the average load factor. These load factors are for the high-load period in winter; the annual load factors were 25.1 and 35.1%, respectively. At that stage, Lipman *et al* [20] had already shown for the England and Wales grid that quite large amounts of wind energy (up to 30 % of demand covered) could be integrated there without incurring large fuel penalties from having to cover for outages with spinning reserve.

In the Portuguese case [21], for additionally installed wind power capacities of 7.8, 18.7 and 30.6 %, respectively, capacity credits of 36.5, 28.9 and 22.9 % of the installed wind power capacity were found, measured against a coal fired power plant with a forced outage probability of 17.3 %. These capacity credits are relatively high, which reflects the high amount of hydropower with reservoirs (2000 MW out of 6300 MW total installed capacity) in the Portuguese system. The integration of wind energy also leads to significant amounts of avoided pollutants.

Quite similar results were found in Denmark [22]: at penetrations of 5, 10 and 15 %, the capacity credits were 30, 25 and 20 % of the installed wind power capacity, respectively. This was compared to a previous study [23], which had found a capacity credit of 23, 16 and 11 % at the same penetrations. They attributed the difference to the "*much better capacity situation*" assumed in the older study.

The high end of the scale is also found in Greece [24]: for 2.5, 5, 10 and 15 % pe[illegible]ation the capacity credit calculated was 38, 27, 20 and 17 %, respectively. The reason for these high numbers is the very high assumed wind energy generation from the turbines: at these penetrations, the load factors were 49.5, 45, 41.3, and 32.3 %. This decrease reflects the economic decisions of wind farm developers to start with the most promising sites and then subsequently to spread to sites with lesser resource. An interesting by-result was that using wind energy in energy saving mode, leaving the replaced plant operational, facilitated higher monetary savings than in capacity credit mode, even including O&M of the plant and investment cost. This is because in the optimised power plant mix including wind energy, the energy savings come mainly from relatively cheap imported coal, while in the existing plant mix wind energy replaced generation from the more expensive fuel oil.

For the Netherlands [25], a previous study had shown the possibility to integrate wind power from 1000 to 1600 MW installed capacity (in a grid of about 16 GW) without recourse to storage and without significant amounts of wind power discarded. In their case, most of the energy from wind replaced energy produced in base load plant. At 1000 MW installed wind power the remaining variations in power output of one-minute values even on a scale of 30 minutes are significant: a change of 500 MW has a frequency of just under 1 ‰. However, van Wijk *et al* [26] did a rather extensive study of the potential power production in the Netherlands, identifying potential sites and using representative meteorological data from 11 sites. They found annual load factors between 19 % and 26 % in a 10-year period. The maximum output attained was 94.5 % of the installed capacity (barring maintenance and forced outages). Some of the losses were attributed to wake los[illegible] They also found that the difference in wind power production between two successive hours never exceeded 40 % in the 10-year period analysed. No reason for this discrepancy could be found from the two studies. Also for the Netherlands, Halberg [27] assumed a capacity credit of 20 % for 5 % of demand covered, while he saw it dropping to 13 % at 15 % contribution.

Using a PreussenElektra model, Consulectra found for Germany [28] a capacity credit of 15 % at 10 % penetration. However, just using the coldest days of the year, the capacity credit dropped to only 6.7%. This feels peculiar, since usually the winds in winter are strongest. They also show a generation duration curve for one site in Ostfriesland (Esens), where the curve for the coldest days shows zero generation in more than 50 % of the time, while in only 30 % of all times during the whole year no generation was found. Earlier, Jarass [29] had shown that a cluster of wind parks on the German coast has a significantly smaller capacity credit when feeding into the (smaller) coastal grid compared to feeding into the grid of all (Western) Germany. The same number of wind power plants distributed over all of Germany displaced even more conventional capacity: 23 % at 15 % of the total demand covered from wind energy.

Another result not quite fitting the overall picture comes from Spain [30]: the capacity credit is calculated as less expansion between 1993 and 2000, and is 10, 16.8, 15 and 15.6 % of installed wind capacity for 1.5, 5, 10 and 15 % penetration. Surprisingly, the capacity credit is not monotonously decreasing, as was the case with most other countries. The reason could be the discretisation of power plants being replaced: at 1.5% penetration, wind power replaces 1 plant of 92 MW, while at 5 % it replaces 2 plant with 550 MW. Therefore, the capacity credit is dependent in their calculations on the expansion plan assumed. All the capacity replaced was newly to be built power plant running on imported coal.
The case of Italy [31] is special, since the resource is good enough for exploitation only in a few selected regions. Hence, the target penetrations were only achieved in relation to the electrical grid in the region. As well, their value for the capacity credit was well below the ones found by the other teams (22.6 % at 0.5 % national penetration, corresponding to 2.5 % penetration in the windy regions).

Fischedick and Kaltschmitt [32, 33] assessed the potential for wind energy in the German state of Baden-Württemberg by using hourly data from 7 stations and spatially interpolating the wind power for every region. Taking the technical potential into account, about 5-8% of the electricity demand of the state could be delivered by wind energy. Analysing the case of a smaller utility with a high percentage of pump storage, they found that the optimal use of wind power is made with a plant mix of small power plants embedded in a grid with large storage capability. However, their result differs from most other results in that wind power mainly replaces power plants in the medium and peak load segment, and nearly none in the base load segment. This could be connected to their rather low load factor for wind energy generation (21.2 and 15.2% for low and medium/high penetration, respectively). Also, the area looked at was comparatively small, and hence the generation very coherent.
Sontow and Kaltschmitt [34] re-did the assessment for three German states and for penetrations from 0 to 20%. The capacity credit drops from ca 24% at 5% penetration to 10% at 20% penetration. The results fall into a wide band of possible results.
Hurley and Watson [35] did another study for the case of Ireland. Wind speed data from Met Eireanns observational network was gathered from 12 stations all over Ireland, and scaled to wind power using a composite of 6 turbines. They investigated three different scenarios, one with 1000 MW well distributed onshore, one with 500 MW onshore and 500 MW offshore, mainly east of Dublin, and one with 1000 MW clustered in the most wind-rich regions in the north-west of Ireland. They investigated the reduction of peak power demand due to the integration of wind power, and found reductions (called in their study a "*crude measure of the capacity credit*") of up to 30 % of the installed wind power capacity for low energy penetrations (5%), and decreasing with higher energy penetrations down to 12-16 % for 30 % penetration. The most distributed generation (dispersed onshore) netted the highest peak power reductions, while the north-west only option was at the bottom of the scale.
Also the Irish TSO calculates in its capacity adequacy report [36] with diminishing returns for increasing wind power in terms of capacity credit. While 400 MW wind in Ireland have a capacity credit of some 25 %, 800 MW installed would decrease it to just over 20 %.

Giebel [37, 38] has shown that a capacity credit assessment of wind energy using a chronological model is difficult, since single events tend to dominate the behaviour of the result. Hereby, the financial benefits from saved fossil fuel are largely unaffected. One way to reduce the insecurity of the displaced capacity is to do a variational analysis, shifting the wind power time series against the load data. Thereby, the variation on a time scale of days is accounted for. The single events most likely to influence the result are when the load is highest, *ie* in central and northern Europe in a seven-week period in January and February. The wind during that period of the year is therefore the most important one for the calculation of the capacity credit. Also Milligan [39] pointed out, that the assessment of a capacity credit by means of a chronological model is highly sensitive to single events. The distribution of the wind during the high-load period is determining the behaviour of the displaced capacity, for small as well as for high penetrations. Since the climatologically average wind speeds during a period are important, no single value for a capacity credit can be given. For small penetrations, the relative displaced capacity will be on average close to the average load factor during the important period. It will scale with the load factor at the time of the highest demand. This is higher in winter, when also the demand is higher. There is a positive correlation between wind speed and demand. Therefore, the determining load factor is higher than the average yearly load factor. For large penetrations, it decreases towards a value depending mainly on the minimum load factor. For a European spatially averaged wind, the unused fossil fuel capacity is down to 9 % of the installed wind capacity at 45 % penetration.

Another result from the analysis is that perfect forecasting does not necessarily lead to a better capacity credit than persistence forecasting. On the other hand, perfect forecasting allows more wind energy to be used in the grid. This behaviour is especially pronounced with very variable wind power generation.

For the relatively smooth average production in Europe, 20 % of the total demand can be covered, while discarding 10 % of the generated wind energy. This percentage of wind energy could probably be used up by effects not modelled in the National Grid Model used for the analysis, such as hydropower reservoirs. At this stage, wind energy would save nearly 60 % of the total fossil fuel cost of electricity generation in Europe, worth close to 7 G€. This would give an estimate of 2.2 €c/kWh as the worth of wind energy in fuel saver mode.

In a study on the implications of the UK governments 20% renewables target for 2020, ILEX and Strbac [40] (see also Dale *et al.* [41]) assessed the extra cost of integration of wind power. They assumed that the first wind power plant would have a capacity credit of ca 35%, *ie* around the average load factor, while for the 26 GW installed in 2020 (60% of which offshore), it would drop to 20%. The grid was supposed to be able to cover the demand in 91% of all years. Their result was that the extra cost for integration was 0.3 UKp/kWh, rising less than 0.1 UKp/kWh for assuming no capacity credit at all.

This work actually is part of a recent trend within the research on large-scale integration of wind power in electricity systems: The question no longer is about the capacity credit for certain (mostly imaginary) penetrations, but rather, in the times of liberalised electricity markets, about the extra cost of integration of the intermittent resource, without explicitly using the capacity credit in the assessment. For example, Parsons *et al* [42] compare 5 recent studies in the US without a separate mentioning of the capacity credit (Xcel Energy in Minnesota, and PacifiCorp and the Bonneville Power Administration in the north-western US). The Utility Wind Interest Group UWIG [43] even expands on this study with a few more cases, again without recourse to the capacity credit.

3.2 The CC in island grids

High wind energy penetration was first examined for the case of island grids, where the installed capacity is typically relatively low. A sizeable proportion of wind power is therefore already achieved with few turbines. Papadopoulos *et al* [44] investigated the cases of Crete and Hios, two Greek islands. They found very high wind power gradients from one minute to the next (up to -62.2 % for one farm, and -38.3 % for three farms on three islands of the Cyclades group, approx. 40 km of each other). They concluded that high wind penetrations in large island could be achieved, as long as the power system as a whole is designed to deal with large wind power fluctuations. A common dispatch centre and wind energy forecasts were deemed essential.

Saramourtsis *et al* [45] showed for the Greek island of Syros that the percentage of wind energy generation accepted into the grid highly depends on the maximum fraction of wind allowed into the grid at any given time. With a 10 % limit, the permitted wind energy already trails off for a penetration of 3 %, while with a limit of 50 %, discarding wind energy only starts significantly at more than 10 % overall penetration. This low attainable penetration might have two reasons: for one, the wind power generation at the different turbine sites was assumed to be identical for all wind turbines, and the available generation consisted of just 5 large Diesel sets, which might be oversized (for reasons of reliability) in relation to the actual load.

Hansen and Tande [46] showed that the modelling approach used for low penetration studies is valid as well at higher penetration. With this aim they did a sensitivity analysis for 2.5 and 25 % penetration for the case of Praia, the capital of the Cap Verde islands, and showed that most parameters did not heavily influence the levelised production cost for the whole energy system, even though the variation width was slightly higher with higher penetration. The only factor to strongly influence the economics of the wind power development was the average wind speed at the site in question. The also claim [47] that for small numbers of wind turbines, the assigned capacity credit has to be reduced due to the fluctuations in output.

Using Markov chain modelling, Torre *et al* [48] set by the limits of wind energy penetration for Corsica to 30 %. However, this was highly dependent on the ratio between installed capacity and peak load. The 30 % limit was reached at 70 % ratio, while for 80 and 90 % nearly no wind energy could be integrated, and for lower ratios, wind energy could easily be integrated up to much higher penetrations.

3.3 Other ways to firm up wind power

The integration of variable sources of energy can also be tackled from the demand side as demand side management. When the demand can react according to the wind power offered, more of the variable source can be used to supply demand. Simple appliances on the residential customers side where the demand can be shifted for at least a few hours include washing machines, dishwashers, freezers and hot water preparation. Most other appliances have only very limited shifting potential (read: shorter than one hour), such as refrigerators or space heating.

The influence of variable pricing on residential customers was assessed in a Finnish experiment [49]. The idea is that if customers are getting clear signals on the actual price of electricity, they can shift some of their loads from peak hours to off-peak hours. They found that only about a quarter of all customers reacted strongly on the variable pricing, hence the potential seems to be limited.

Having access to electricity at varying market prices, the savings possible by deferring the charging of electrical cars were estimated by Nielsen *et al* [2] to be in the range of 11 €/a. Therefore, the incentive given is very low.

Currently (2004), the FIRMWIND project [50] looks at the possibilities to improve the capacity credit of wind energy, taking into account everything from the wind on-site all the way through to the load. They have a test case of two islands, and state as their first result that a modest amount of storage is utilised better with a load-smoothing approach than as a compensation for windless periods.

Cavallo [51] argued already much earlier for a firming-up of wind power with either Compressed Air Energy Storage, or just by increasing the load factor of the wind power plant through installation of larger blades for the same generator size, thus being able to use lower wind speeds for electricity generation.

While not exactly connected to the capacity credit, Bolinger and Wiser [52] estimate the hedging value of renewable energies to be roughly 0.5USc/kWh. Their method was to look at the financial tools available to hedge against the 10-year gas price risk.

4 A Note on Smoothing Effects

As we have seen in the previous chapter, the capacity credit is typically connected to the actual wind power production at the times of peak load, and trails off for large penetrations towards a value determined by the minimum wind power production. Harvesting wind power over a larger area is statistically bound to increase the minimum production at these times. Essentially, the argument is that there is always some wind somewhere. Therefore it is relevant in the context of capacity credit considerations, to also connect it to the size of the wind power production area and the variability, or smoothing, of the resulting wind power time series.

The integration of wind power into an electrical grid is easier if the variations in the wind power are happening on a long time scale. While single wind turbines can swing between 0 and 100% production, wind power harvested from a large region hardly behaves like that due to the weather patterns' spatial variability. A front passing over an area will also lead to high power gradients at a single turbine, but since the passing of the front does not happen at the same time for all wind farms in a larger area, the wind power gradients are smaller with distance. Mathematically, this is related to the cross-correlation between the wind power time series. If the correlation is high, the wind power tends to swing in synch. If the correlation is low, then the variations in power output are more randomly distributed over time and tend to wash each other out.

Landberg [6] did an analysis of 58 sites distributed all over Europe. The same data was later used by Giebel [37] – his study's results were quoted above. An exponential fit of the form CrossCorr = exp(-Distance/D) to the data yields a scale parameter D being 723km. Landberg found that the European mean wind has a more narrow distribution than any single wind power frequency distribution. The variability (measured as standard deviation divided by the mean) is also greatly reduced in comparison to any single wind power site.

Cross-correlations have been published for the case of Ireland [53]. While only showing data up to 400 km distance, the scale parameter of the correlations is consistent with the roughly 750 km quoted above.

The probably best-known ensemble of wind farms in that respect is the one measured under the WMEP (Wissenschaftliches Mess- und Evaluierungs-Programm) of the ISET (Institut für Solare Energieversorgungstechnik). Ernst [54] did an analysis in regard to ancillary services of the smoothing. He investigated both smoothing between a cluster of wind farms a short distance away, and larger distances up to a few hundred km. His main result is that the correlation between different wind power time series is dependent on the time period in question. For 5-min averages, the correlation drops to zero already for few tens of kilometres, 1-hour averages drop to very little already after less than 100 km, while the 4-hour and 12-hour averages correlate on much larger distances: the 12-hour averages drop to 1/e at about 300 km.

Wind power fluctuations on the scale of The Netherlands have been investigated by van Zuylen *et al* [55]. From 5-min data from 7 wind farms distributed over the country, they could show that the ramp rates for the "Dutch wind farm" were significantly lower than for individual wind farms.

Milligan and Artig [56] investigated smoothing and capacity effects of 7 sites in Minnesota over a three-year period. They developed a method based on fuzzy logic to determine the optimal installation per site to best use the smoothing effect. By just combining the output of equal installation sizes at all sites, they report a reduction of the coefficient of variation in a 6-hour window of 20-40 percentage points. One caveat was that the optimal distribution of capacity over the sites depended heavily on the year used. Quote: "*The wide range of results is slightly distressing.*"

An impressive amount of data has been collected by NREL and (then) Enron Wind, as reported by Wan and Bucaneg [57]. They used secondly data from two large wind farms to assess the statistical distributions of the short-term fluctuations of the single and the combined power output. Together with the expected result of only a narrow band of variations, they also show evidence for a time-lagged similarity in output depending on wind direction, when large weather systems cross the area.

Poore and Randall [58] investigated the ramp rates of three clusters of turbines, 4 and 8 km from each other. They found that even from one 10-min period to the next, there was less than a 5 % chance for a change in output of more than 10 %.

A recent study that attracted quite some attention was done by Archer and Jacobson [59] of Stanford University. Despite having data from 1327 land based measurement stations and 87 radiosonde soundings for the year 2000, they only used data from eight stations in an area of about 550 x 700 km^2 to find that the probability of no power over a 4-hour period became zero, and generally the distribution for four-hour blocks narrowed with larger area considered.

Another new result comes from Balea *et al* [60] for France. Using three years of wind speed data from 40 probable locations all over the country, they created 9 different installation scenarios. Different power percentiles were assessed depending on the spreading out of wind installations. The scenario with the lowest spread (everything in one region) had a 5 % probability to drop below 1 % of the installed capacity, while every other distribution of wind power installations over the whole country yielded 3.3-4.8 % at this probability level.

The largest study to date was done by Holttinen [61, 62] for the Nordic countries. In the first part, she analyses the variations and time scales for the four Nordic countries (DK, SE, FI and NO) for representativity. An interesting new result is the following: "*From the available hourly time series for Denmark, guidelines for the statistical properties of large scale wind power were made. An hourly time series of large scale wind power production should have standard deviation of the production series less than 20 % of capacity, maximum hourly production less than 100 % (85...95 % depending on how large the area in question is), duration of calms limited or non existent, standard deviation of the hourly variation series less than 3 % of capacity and the hourly variations in between ±20 % of capacity, or even less if the area is larger than the size of Denmark (300 x 200 km^2)*". In the second part, she estimates the impact this smoother wind power generation profile has on the Nordic electricity system and market on the hourly scale. She concludes, "*If the Nordic electricity market area would be working without bottlenecks of transmission, 10 % of wind energy distributed in the area would require extra flexibility of less than 1 % of installed capacity.*"

Nørgård and Holttinen [63] recently proposed a technique to take these smoothing effects into account, when only limited wind time series information is available. Their multi-turbine power curve approach smoothes out the power curve, to account for the effects of moving weather patterns and the correlations between wind turbine clusters at different sites. It might not be the optimal solution, but it makes work possible with only very few data sets.

The network strengthening properties of distributed generation are especially apparent in remote areas with weak networks and high resources. In rural India for instance [64], building high power grids is rather expensive, while area for renewable generation is not an issue.

Lakkoju [65] generated joint distributed probability density functions for the combined generation of offshore wind power with onshore wave power devices. The combination yielded a higher probability for generation at medium and high output than the two generation options alone.

5 Summary

Wind energy has a capacity credit. All the about 50 studies catalogued here, done by public research institutes, private consulting companies and electrical utilities, support this statement. The capacity credit is depending (among other things) on the load factor and the penetration. It tends to decrease from approximately the load factor for small penetrations to some 10-15 % at high penetrations. It is highly dependent on the electrical system used for comparison, especially the amount of storage possibility and the match of load and demand. A proper assessment needs hourly load and wind power time series, although some shortcuts exist to give a reasonable estimate. Wind energy predominantly replaces base load plant, since more flexibility in the system is needed to accommodate wind energy.
The concept of the capacity credit had its heyday in the eighties. Since then, it got quiet around it, as people thought that the markets would react properly towards capacity expansion. In recent years, some renewed interest exists, but the question in most recent studies has been after the cost of integration of wind power, without proper recourse to a full capacity credit assessment.
Does that mean the capacity credit is dead? Not as long as public perception still has it as one major obstacle to wide-spread adoption of wind power.

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