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EFFECTIVENESS OF POLICIES AND STRATEGIES TO INCREASE THE CAPACITY UTILISATION OF INTERMITTENT RENEWABLE POWER PLANTS

This paper presents evidence on the effectiveness of different strategies and measures to increase the capacity utilisation of wind and other intermittent renewable energy plants. The report has been prepared by David Benatia (Université de Montréal), Nick Johnstone and Ivan Haščič (both OECD Environment Directorate).

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This work was initially conceived as primarily a contribution to the OECD's work on "Trade and the Environment" (PWB Item 3.1.3.2) assessing the benefits of liberalised electricity trade on the capacity utilisation of intermittent renewable energy plants. In the course of doing this work it became clear that this relationship could not be examined in isolation and that the effects of other factors needed to be taken into account.

This paper has been prepared by David Benatia, Nick Johnstone and Ivan Haščič (OECD Environment Directorate). A draft of this report was reviewed by delegates to the Working Party on Climate, Investment and Development at their September 2012 meeting. The paper was also presented to June 2012 meeting of the Joint Working Party on Trade and the Environment. It has benefited from the comments received.

A companion report focussing on the trade aspects ("Cross-border Trade in Electricity and the Development of Renewable-Based Power") has been prepared by Heymi Bahar and Jehan Sauvage and has been presented to the Joint Working Party on Trade and the Environment (COM/TAD/ENV/JWPTE(2012)20). That report includes simulations based on the model presented in this document.

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EXECUTIVE SUMMARY

Many OECD governments have established ambitious targets for the penetration of renewable energy. Wind and solar power are the renewable energy sources which are growing the fastest and which will have to become increasingly important elements in the electricity supply mix if ambitious targets are to be met. However, the generation of electricity from these sources is variable and unpredictable. This combination of variability and unpredictability, termed intermittency, poses significant challenges for grid operators since electricity supply and demand needs to be in balance on a continuous basis.

While investment in a wide portfolio of renewable energy sources and the spatial dispersion of their location can reduce the risk of loss of load by reducing the correlation in their peaks and troughs, this is not likely to be sufficient as penetration rates rise. Investment in increased capacity of intermittent electricity power sources needs to be complemented with other measures in order to reduce the risk of loss of load and maximise the use of installed intermittent renewable power capacity.

In particular, measures that increase grid flexibility and transmission capacity are keys to ensuring an efficient use of the intermittent renewable capital stock. Grid flexibility can be achieved through the use of dispatchable power plants (principally gas and hydro), but also energy storage facilities (pumped hydro and advanced energy storage), and advanced grid management (including smart grid technologies). Increased transmission capacity through investment in high-voltage transmission lines allows for the more efficient exploitation of widely-dispersed generating sources within the grid. This can be complemented with high-capacity interconnectors which allow for the greater integration of grids (including cross-border trade).

In this study we have assessed the effect of these different factors on the capacity utilisation of wind power plants. The model developed here focuses on wind energy since it is the most widely deployed, variable and unpredictable among intermittent renewables. However, the analysis is of broader relevance since it also applies to other intermittent renewable power source – i.e. solar photovoltaic and marine. Two samples are estimated over the period 1990-2009, 21 European countries and a broader sample including ten other OECD economies.

A measure of available wind power was constructed based on monthly observations of average wind speed at wind power plants. A number of other explanatory variables which are subject to policy intervention are included, namely: i) dispatchable power; ii) storage capacity; iii) transmission capacity; and iv) electricity trade. In all estimated models the different explanatory variables of interest are interacted with dummy variables reflecting the extent of capacity penetration of wind power.

While grid capacity and dispatchable power are found to have a relatively stable impact on plant capacity utilisation for different capacity penetration rates, it is found that energy storage (pumped hydro) has an increasing impact on wind plant capacity utilisation with increasing capacity investment. In the case of electricity trade the effect only becomes statistically significant once a penetration rate equal to the upper threshold is exceeded. However, this is equal to 3% penetration (for the European sample), indicating that trade will have positive consequences for most countries as target objectives are approached.

The results of the model have important implications for the efficacy of different measures adopted to facilitate the integration of intermittent renewable energy plants in the grid. Further work will assess the costs and benefits of policy incentives which influence the different power balancing strategies. However, some general conclusions can be drawn from the results presented thus far. As the penetration of intermittent renewable increases it is necessary to:

- Ensure investments in quality and capacity of the grid keeps pace with investment in intermittent renewable generating capacity;
- Provide incentives to allow the owners of dispatchable power plants to receive the option value associated with their availability as balancing power and strategic reserves;
- Encourage energy systems integration (e.g. CHP) and demand management (i.e. smart meters) as a means to help balance supply and demand;
- Reduce existing constraints on trade in electricity (including those which arise out of renewable energy support policies); and,
- Encourage the continued innovation in advanced energy storage and grid management technologies.

This report sheds light on the benefits (in terms of capacity utilisation) associated with different strategies. The policy challenge is to ensure that incentives across these different strategies are aligned. The benefits in terms of IR capacity utilisation associated with each strategy will vary and this should be reflected in the different mechanisms at the policymakers' and regulators' disposal. This includes network user charges, financing of investments in interconnectors, capacity payments for balancing power and strategic reserves, public R&D support for advanced grid management and storage, programmes to encourage diffusion of smart meters, etc… Increased penetration of IR sources requires a rebalancing of policy efforts, perhaps with less of an exclusive focus on direct support measures for IR electricity generation (i.e. feed-in tariffs and renewable portfolio standards).

EFFECTIVENESS OF POLICIES AND STRATEGIES TO INCREASE THE CAPACITY UTILISATION OF INTERMITTENT RENEWABLE POWER PLANTS

1. Introduction

A number of OECD countries have committed to self-established ‘renewable energy targets’ as objectives to generate a given share of total energy consumption from renewable energy sources (RES). The European Union (EU), for instance, has for objective to produce 20% of total gross energy consumption from renewable energy sources by 2020. Renewable energy targets focus on the electricity sector in particular, as it is both carbon-intensive and appropriate for the deployment of renewable technologies.[1] For example, the European Renewable Energy Council estimates that 33% of total electricity consumption in the EU should be generated from renewable energy sources in order to meet the objectives by 2020 (EREC 2008). The International Energy Agency evaluates that wind and solar photovoltaic (PV) alone should provide 30% of global electricity by 2050 in order to meet the target of halving greenhouse gases (GHG) emissions (IEA 2009). In an effort to meet these objectives many governments have implemented support policies for the development of renewables in the energy sector.

Among renewable energy technologies, wind and solar are the fastest-growing in OECD countries with an annual average growth rate in installed capacity of respectively 26% and 44% between 2000 and 2009.[2] However, the large deployment of wind, solar, and marine energies in the power sector raises concerns in terms of supply reliability because of the intermittent nature of generation from these sources. They depend on exogenous ecological conditions which are variable in intensity, such as local solar irradiation or wind speed. Moreover this variability is imperfectly predictable despite increasingly refined forecasting techniques.[3] As a result, the output generated by those types of power plant is variable and somewhat unpredictable. Additionally, the variation in supply may be negatively correlated with peak load demand.

Power is quite an unusual type of good as it cannot be stored at reasonable costs and thereby requires input to equalize output at any point in time. On the one hand, in order to avoid loss of load (and significant downstream economic impacts) grid operators must guarantee electricity supply at almost 100% for any level of demand at any time. On the other hand, the provision of excess supply can undermine the stability of the grid. The variability introduced by intermittent renewable (IR) energy source on the supply side of the market may put the security of supply in jeopardy, if the power system cannot adapt to their variable delivery profile. As a consequence, the diffusion of IR energy sources in the electricity market complicates the task of the grid operators. Other power plants are required to more or less adjust their output according to that of intermittent renewables. Such balancing power is absolutely necessary to allow for the penetration of renewable technologies.

Power system flexibility and transmission capacity are the two key components required for the grid to be able to integrate intermittent renewable electricity.[4] System flexibility refers to the capacity of the

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[1] In particular wind and solar photovoltaic technologies as they do not use steam-fed turbines as is the case with geothermal and biomass technologies that may also be used to produce heat.

[2] Estimates derived from IEA Statistics (2011).

[3] According to Ackermann et al. (2009), it is not realistic to expect day-ahead wind forecasts to become accurate enough for detailed day-ahead planning of wind plant production schedule.

[4] “Flexibility is the right response to the intermittency challenge of renewables” (IEA 2011a). “A key issue that will determine whether significant levels of wind power can be added is the availability of new transmission” (Fink et al. 2009).

grid to adapt to the variable and uncertain delivery profile of intermittent renewable (IR) plants, such as wind or solar PV plants. Transmission capacity relates to strength of network infrastructures for transmitting electricity, preventing congestion, and dealing with sudden large changes of power input in the system. The requirements in terms of system flexibility and transmission capacity increase with the penetration of intermittent renewable power entering the grid. Therefore, countries targeting high penetration of such renewables in the near future will need both strong and flexible grids.

Indeed, in the absence of such investments curtailment of intermittent renewable power is foreseen to increase dramatically with the penetration of IR energy sources in the electricity sector.[5] IR power plant capacity utilisation will be constrained below what the natural resource would effectively permit because of a lack of grid capability. Even if ecological conditions allowed for generation in principle, large amounts of the IR power plant capital stock will be unused at any given point in time. This is of major concern since it affects a country's capacity to meet its renewable energy objectives, which are expressed in terms of percentage of power generated. More IR generation capacity would be required to produce the same quantity of low-carbon power. Therefore, society might incur much larger costs of meeting its renewable targets if the grid is not adequately developed in parallel with increased IR generating capacity.

Allowing the power system to handle larger quantities of intermittent renewable power can be done through two complementary sets of strategies. First, the power network infrastructures may be reinforced by investment in transmission and distribution lines. This allows for the integration of IRP into the network, but also lets distant flexible resources reach demand centres when required. Second, additional flexibility may be introduced into the system by deploying 'dispatchable' power plants, such as gas-fired plants and hydro plants which are able to adapt to the intermittent delivery profile of wind and solar plants. Other sources of flexibility are to be found in energy storage plants and technologies that improve malleability of the demand side ('smart' grid technologies). The effects of intermittency may also be alleviated by the increased geographic dispersion of IRP source and investment in a diverse portfolio of intermittent renewables. Both of these will reduce the correlation of power output from available IR energy sources.

And finally, international trade in electricity can play an important complementary role with respect to all of these strategies. Firstly, it increases the spatial dispersion and portfolio diversity of IR energy sources, resulting in reduced correlation amongst them. Secondly, it gives greater access to complementary dispatchable sources and energy storage facilities (including pumped hydro). And finally, it may reduce correlation in peak demand, particularly if interconnections cross time zones.

Therefore, achieving increased penetration rates of intermittent renewable cost-efficiently requires managing a whole portfolio of variables, such as improving the flexibility of national electricity grids and enhancing transmission capacities. In the absence of sufficient transmission capacity, grid flexibility and electricity trade OECD countries will not be able to make effective use of the intermittent renewable capacity in which they are currently investing. As penetration rates increase, the challenge becomes even greater with the need to 'balance' an increasingly large share of the grid's portfolio. In the absence of complementary policy initiatives plants will lie idle, even when wind and other ecological conditions could, in principle, allow for the generation of electricity.

Based on an empirical analysis, this paper seeks to provide guidance on the optimal design of policies supporting RES deployment. The study focuses on wind power plants in order to shed light on the different production constraints, but the lessons learned are of relevance to all types of IR energy sources. We first estimate the respective effect of dispatchable generation, transmission capacity, cross-border electricity trade, and energy storage on wind plants capacity utilisation for a given annual wind resource, using annual

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[5] See Fink et al. (2009), Rogers et al. (2010), Ela (2009), Denholm and Hand (2011).

data for 31 OECD countries over the period 1990-2009. Then, we evaluate how those effects vary as the penetration of wind power increases. Our findings suggest that all those factors influence wind plants' effective capacity utilisation, although to differing extents and at different penetration rates.

Section 2 reviews the links between the penetration of intermittent renewable energy and the capacity utilisation of the plants. Section 3 presents the key roles played by grid flexibility and transmission capacity in allowing for greater use of installed intermittent capacity. Section 4 presents the data and model used in the empirical analysis, and summarises the main results. Section 5 proposes a simulation of European wind power penetration rates through 2020 for different levels of grid transmission capacity. Section 6 concludes.

2. The Capacity Utilisation of Intermittent Renewable Plants

Output from individual plants can vary on a scale of seconds to minutes, as well as over several hours. In a sense, all plants have 'variable' output, insofar as there is some probability of an incident which puts the plant off-line for a period of time. Since unforeseen power outages can impose significant economic costs, most regulators have a target "loss of load probability" (LOLP). For instance, in the United Kingdom this is set at nine (i.e. nine outages per century). This is met by building in a system margin, allowing the system to meet unexpected decreases in supply from some plants and/or unexpected increases in demand.

The introduction of intermittent renewable energy plants increases the required system margin in order to meet the target LOLP (Neuhoff 2005). This is because their output is variable, unpredictable and correlated.[6] The extent to which they can contribute to peak demand can be measured as "capacity credit" – i.e. the amount of electricity (expressed in terms of conventional thermal capacity) that can be served by intermittent plant without increasing the LOLP. For instance, while wind plants generally have a capacity factor in the region of 20% to 40% (relative to 80%-90% for conventional fossil fuel-fired plants) the capacity credit is less, reflecting the variability and unpredictability of output through time. At 20% wind power penetration, Gross et al. (2007) estimate a capacity credit of 19%-26% for a plant with an average annual capacity factor of 35%. On the basis of a formula developed by Gross et al. (2007) this can be converted into a 'reliability cost'[7] of approximately £4/MWh, which can be considered as an 'externality cost' arising out of intermittency. As penetration levels of intermittent renewables rise still further the ratio between capacity credit and capacity factor falls, reflecting increased vulnerability of the system. The extent to which the penetration of intermittent renewables increases LOLP is a function of the flexibility of the system.

This study focuses on the factors affecting the capacity utilisation of intermittent renewable generators - that is how much power is actually fed into the grid by intermittent renewable plants with respect to installed generation capacity. In this paper, we use the term "effective capacity factor" (*ECF*) as a measure of IR plant capacity utilisation at country level. We define it as the annual quantity of power dispatched from plants of a certain technology into the network with respect to total installed generation capacity of that specific technology at country level, i.e. actual relative to nominal wind power production (where nominal production equals total installed wind generation capacity multiplied by number of hours in the year). In the case of wind technology, *ECF* is basically the average of the annual capacity factor of each installed wind turbine weighted by their respective nameplate capacity.

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[6] Note, however, there are some 'intermittent' variables which correlate with peak demand (e.g. solar photovoltaic and air conditioning). See Heal (2009) and Gross et al. (2007).

[7] The difference between the fixed cost of energy-equivalent thermal plant minus the fixed cost of thermal plant displaced by capacity credit of the intermittent plant.

This paper focuses on the particular case of wind energy to illustrate the importance of different factors in allowing for the increased penetration of intermittent renewable energy in the power sector. Wind energy is the most variable, unpredictable, and most widely deployed of the intermittent renewable energy sources. Therefore any factor that negatively affects wind plants capacity utilisation today is likely to be a constraint for other technology types such as solar farms and wave-snakes in the near future.

Effective capacity factors are derived from IEA statistics, using annual data by country on electricity generation (in GWh) and installed generation capacity (in GW) by technology. Since no accurate historical monthly data were found on commissioning (and decommissioning if applicable) dates for wind turbines of interest, we assume all new plants to be systematically commissioned on the 1st of January every year. Given the nature of the study this approximation should not affect our results appreciably. Figures 1 to 4 display respective *ECF* time-series for four OECD countries from different geographic regions although all endowed with a large wind power generation capacity relatively to their respective power sector. The effect of spatial dispersion of wind generators may be noted from Figure 3, the volatility of *ECF* decreases in New Zealand as larger wind generation capacity is available.[8]

The major constraint to IR electricity generation is undoubtedly the natural resource itself. A wind turbine cannot produce any power if the kinetic energy of wind is not sufficient, and a solar plant cannot produce solar power if sun is not shining. The consequences of this uncertainty can be reduced through portfolio diversification of IRP. As long as the different ecological factors (wind, sun, waves) are less correlated across than within different factors, broadening the basket of IR energy sources lowers the aggregated risk (reduced production variance), and enables IRP to displace more conventional plants thanks to a smoother delivery profile. It has been found that output across IR power plant types must be approximately equivalent in scale for technological spread to have a significant effect on aggregated fluctuations (IEA 2011a).

Geographic dispersion of intermittent renewable generators (by technology type) also reduces the total variation for a given installed generation capacity. For instance, Sinden (2007) finds that hourly correlation coefficient across UK wind farms falls to 0.1 when distance is greater than 100 km. Drake and Hubacek (2007) estimates through a risk portfolio simulation-based approach that wind power variability in the UK may be reduced in the order of 36% as a result of dispersing wind generators over the territory. Roques et al. (2010) uses the Mean-Variance Portfolio theory to model the optimal wind power spatial deployment in Europe. In line with TradeWind (2009), the analysis suggests that large efficiency gains may be achieved through better coordination at the EU-scale, thanks to renewable credit trading across countries and alleviated cross-border network constraints.

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[8] Extreme values have been dropped out of the data set for statistical reasons.

Figure 1. ECF time-series for the United States (1990-2009)

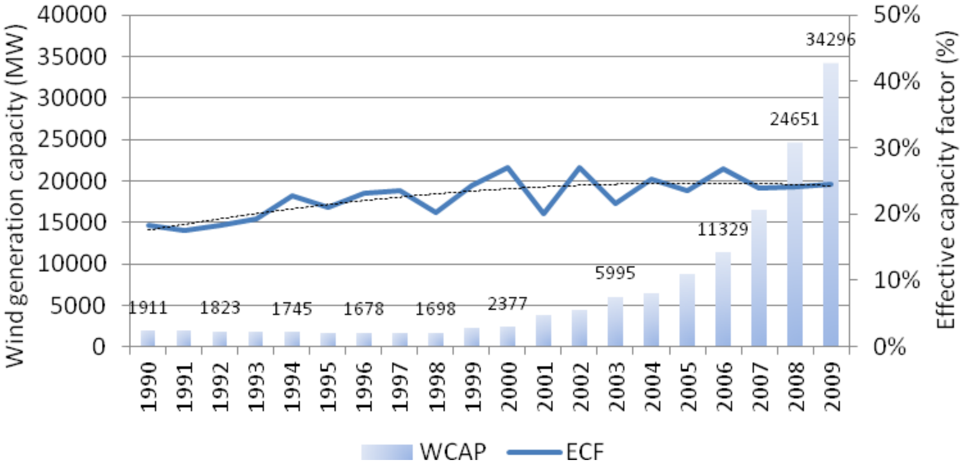


Figure 2. ECF time-series for Denmark (1990-2009)

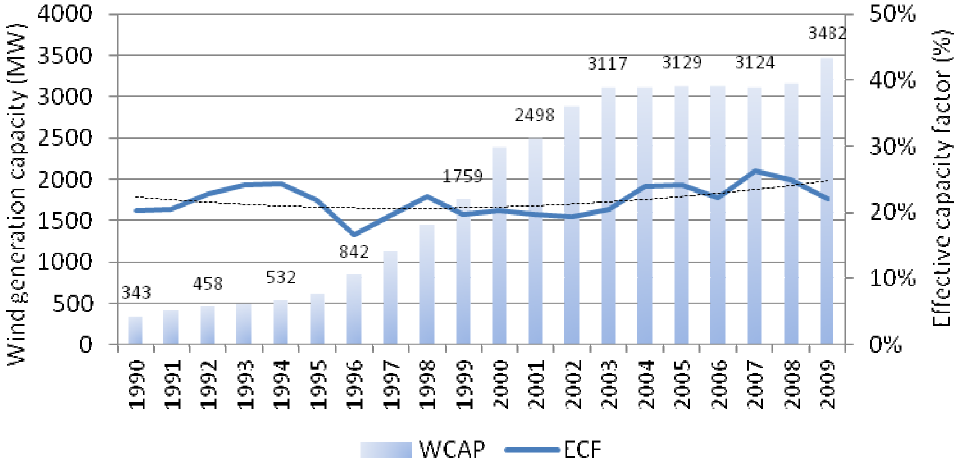


Figure 3. ECF time-series for New Zealand (1997-2009)

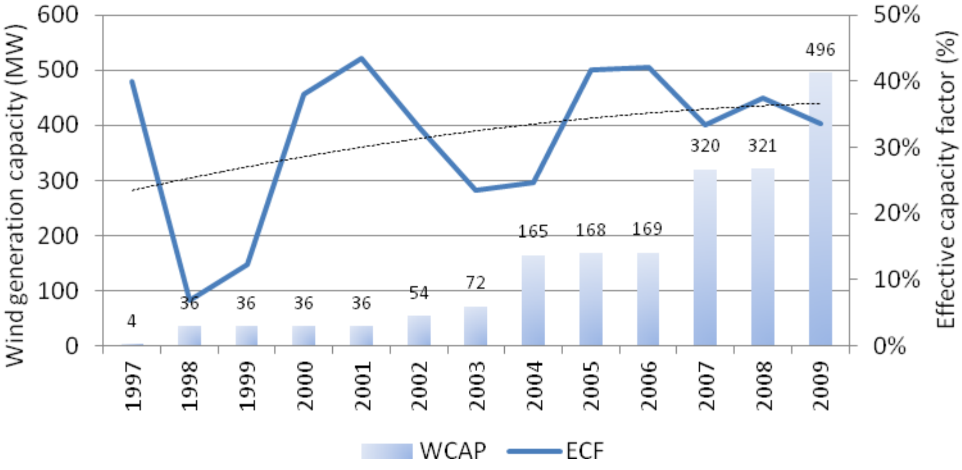
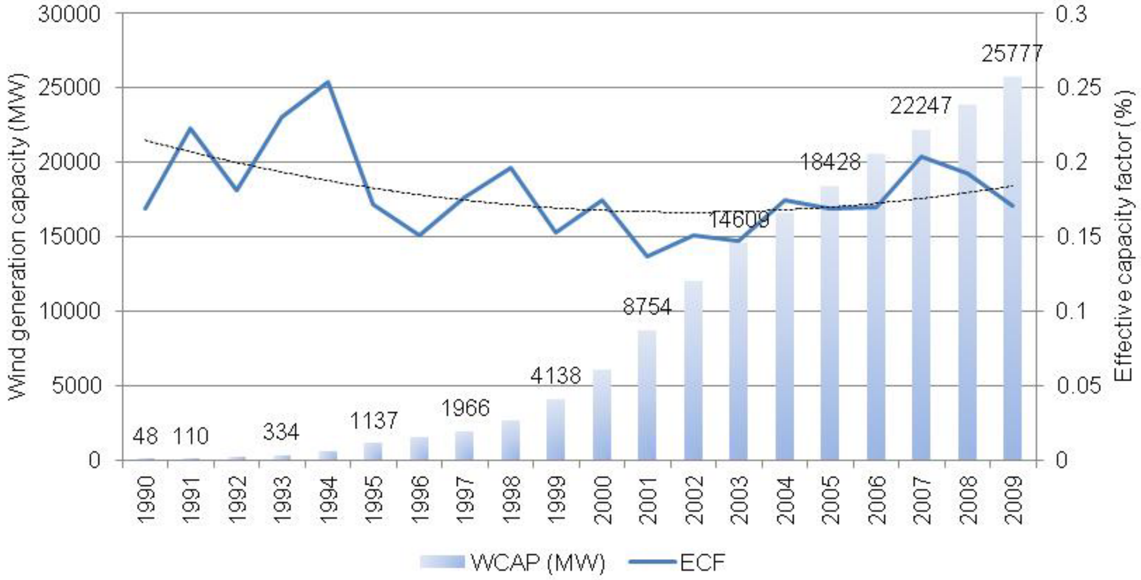


Figure 4. ECF time-series for Germany (1990-2009)



3. Strategies to Facilitate Grid Integration

3.1. Transmission capacity

As noted above, the extent to which the grid as a whole can accommodate intermittent renewables is a function of its capacity to adjust to supply and demand shocks (power system flexibility). Such capacity needs to increase along with the penetration of intermittent renewable sources, so that IRP capacity utilisation is secured by adequate system flexibility (IEA 2011a). However, for a given flow of renewable energy – though dispersed across space and allocated across sources - several other factors are crucial to allow for the economic exploitation of the power generated. First of all, an increase in IR generation capacity may result in lower overall IR power plant capacity utilisation due to inadequate transmission capacity which restricts integration. IR power plants, in particular wind plants, are typically located at some distance from demand centres and require new transmission lines for grid integration. The planning horizon for the construction of transmission lines is generally much longer than for wind power generating projects,[9] partly due to heavy administrative barriers.[10] The installation of new transmission infrastructures lagging behind that of intermittent renewable projects raises concerns in terms of grid integration (Ela 2009).

The benefits of improved transmission capacities are potentially significant because they decrease the frequency of curtailment practices, and hence improve grid integration of IR energy sources.[11] For instance, the average annual wind curtailment in the US Texas grid, Electric Reliability Council of Texas (ERCOT), was about 16% in 2009, essentially due to limited transmission capacity.[12] In 2008, ERCOT has

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[9] According to AWEA-SEIA (2009), transmission lines require 5 years to be built while renewable generation projects need less than a year.

[10] See http://www.windbarriers.eu/ for detailed information.

[11] See, Rogers et al. (2010) for detailed examples of wind energy curtailment practices in the US, New Zealand, Ireland, Germany and Spain. Case studies on wind curtailment practices are presented in Fink et al. (2009).

[12] Whereas only 0.08% of overall wind power production (74 GWh) were curtailed in Germany between 2004 and 2006.

estimated that an investment of $3.8 billion in grid infrastructures would allow savings of up to $1.2 billion in fuel costs each year, due to the new wind energy brought online (AWEA-SEIA 2009). In the same vein, EWIS (2010b) lists 150 grid reinforcement projects; with an indicative total capital cost of €12.3 billion,[13] necessary for a "successful integration" of wind power into European electricity networks under the EU 20% renewable target. The International Energy Agency estimates that more than $100 billion (2010 US$) will be invested in transmission and distribution infrastructures in OECD countries throughout 2011-2035 for renewable integration purposes only (IEA 2011b).

IRP are generally built in rural areas and require new transmission lines to reach load centres. Their concentration in areas with large natural resource availability further worsens congestion issues and exacerbates transmission shortages.[14] While grids need reinforcement of high-voltage transmission capacity, a wider geographic dissemination of IRP may contribute to reducing grid congestion associated with capacity concentration. On top of that, stronger networks may relieve existing transmission constraints on flexible resources and improve the overall system flexibility (IEA 2011a).

3.2. System flexibility

The power system requires a certain flexibility to accommodate IR electricity generation. The primary source of flexibility in grids is typically dispatchable power generation. The existence of sufficient dispatchable capacity is required to cope with the intermittency of wind and solar since they can adapt to variable delivery profiles. An increase in dispatchable generation enhances the inherent capability of the grid to deal with intermittent renewables by bringing extra flexibility on the supply side of the system. 'Dispatchable' power plants are those with the ability to ramp output up and down (or be switched on and off) within the necessary timeframe and at reasonable costs. In principle all plants can be ramped up and down if time and resources permit. However, given their engineering characteristics gas-fired and hydro plants are the two primary sources of dispatchable power.[15]

Unfortunately, in the absence of appropriate incentives, the economic viability of dispatchable plants with sufficient ramping capacity is unlikely to increase along with the diffusion of IRP. In effect, their capacity factor (actual use) falls as penetration of intermittent renewables rises, since they are used increasingly as a complement to IR power plants (referred to as "compression effect"). For that reason, the economic viability of dispatchable generation projects will decrease unless this 'option' value is reflected in their returns. Mechanisms need to be put in place which would reflect the system-wide value of dispatchable plants' ability to ramp power up and down. Ambec and Crampes (2012) show theoretical evidence of this limitation, and propose cross-subsidies from the intermittent source to the dispatchable one and/or structural integration of the technologies as two possible ways of addressing this issue. Alternatively, Joskow (2008) discusses capacity payments for dispatchable plants (see Box 2 for a discussion.)

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[13] EWIS (2010a) demonstrates that the potential benefits of grid reinforcement projects outweigh the costs.

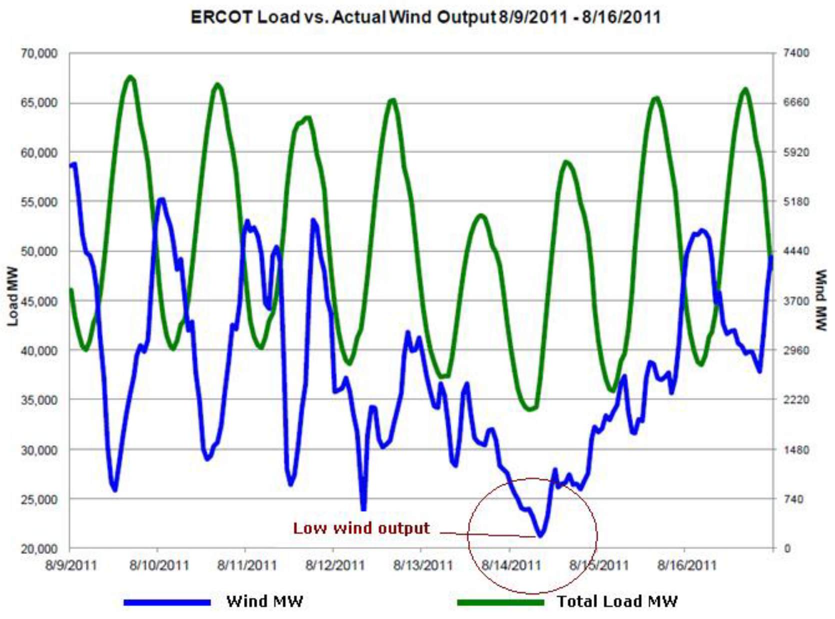
[14] For instance, Scotland contains more than 61% of total onshore wind generation capacity in the UK (Source: http://www.bwea.com/statistics). The UK parliament has recently been proposed with two additional Scotland-England interconnections, following a study of the Electricity Networks Strategy Group, in order to deal with grid congestions due to the high penetration of wind power in Scotland. (http://www.publications.parliament.uk/pa/cm201012/cmselect/cmscotaf/writev/robust/rg011.htm)

[15] See IEA (2011a) for a more detailed description of dispatchable generation sources and associated flexibility. Interestingly, base-load power plants, such as nuclear and coal plants, are often capable of providing helpful flexibility although they cannot be the only resource when dealing with significant diffusion of IR energy sources in the supply mix.

Box 1. Curtailing and Ramping in Texas, USA

The consequences of wind power intermittency have been acute in Texas. When wind electricity production is too high relative to demand, there may be congestion, threatening the security of the grid. When this arises, regulatory authorities curtail electricity production from wind plants. In Texas, congestion was such a problematic issue that the regulation authority (ERCOT) had to put generation limits into place, curtailing 16% of wind electricity generation in 2009, with regular peaks of more than 30% daily. At other times, the wind does not blow when it is most needed. The generalized use of air conditioning means that demand peaks are positively correlated with temperature peaks. In fact, the heat wave that struck the state in summer 2011 – a 38°C peak almost every day in August - coincided with very low winds, a common occurrence. Hence, wind turbines could not help provide electricity to the grid. In response, the grid operator brought four mothballed gas-fired units back online on August 16th (see Figure below). To tackle these issues the improvement of transmission and storage capacities, as well as increased inter-grid trade, seems crucial in Texas. While discussions are underway on the latter point, connections with other grids remain limited.

Figure 5. Load vs Actual Wind Output during Heat Wave in Texas 2011



Sources: S. Fink et al. (2009) - Wind energy curtailment case studies and ERCOT Grid Operations Wind Integration Report 08/16/11- *http://www.ercot.com/*

Box 2. Option Values for Flexible Generation and Capacity Remuneration Mechanisms

Capacity remuneration mechanisms (CRMs) have been introduced in the past in order to overcome shortcomings in the market that result in insufficient generation capacity availability. The primary motivation has been to ensure that there are sufficient incentives for investment in the face of market and regulatory uncertainty. Under such schemes plants are remunerated not only on the basis of their electricity output, but partly also on the basis of their capacity availability. According to EURELECTRIC, these CRMs can take a variety of forms, including:

- Capacity payment: pays a fixed amount for available capacity to all generators. The level of payment is set by a central body, rather than through a competitive process.
- Tender for targeted resource: capacity payments are only given to resource needed to make up for any shortfall in the market. The level of payment is set through a competitive tendering process. This has been implemented in Sweden in extreme peak market conditions.
- Capacity obligation/ticket: an obligation on suppliers to contract with generators for a certain level of capacity determined by the transmission system operator/regulator.
- Capacity auction: the capacity volume is set centrally for a number of years. The price is determined by auction. This mechanism is currently used in some markets in the USA.
- Reliability option: this model is also based on a forward auction, but as a financial market instrument (a “call option”) rather than a physical instrument; generators must be available to the system operator for dispatch above a defined strike price. This model has been implemented only in Colombia.

Such mechanisms have not usually been designed with the objective of specifically providing balancing power for intermittent renewable sources. However, with rising IRP penetration rates it is becoming increasingly important to ensure that the proposed mechanisms also remunerate the ‘option value’ associated with the existence of flexible generation capacity necessary to cope with a large share of IR energy sources.[16]

Source: *www.eurelectric.org/download/download.aspx?DocumentFileID=68526*

Energy storage also increases flexibility by allowing for a temporal smoothing of the delivery of energy generated. While several technological options are being developed, in practice pumped hydro is by far the most important type of energy storage and has proven to be very useful to smooth supply fluctuations introduced by IR power plants. A large pumped storage capacity is available in some countries

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[16] Interestingly, the Electricity Authority of New Zealand has been concerned with the medium- and long-terms implications of non-price rationing mechanisms (i.e. load shedding) in the face of emergencies. The fear is that the price suppression arising from such will discourage investment in the generating capacity needed to ensure that such emergencies do not recur. See Scarcity Pricing - Proposed Design consultation paper (http://www.ea.govt.nz/our-work/consultations/priority-projects/scarcity-pricing-arrangements-proposed-design/)

with suitable ecological conditions, such as Norway and the United States.[17] (See Box 3 for a discussion of an innovative solution being developed in the Canary Islands.)

Box 3. Benefits of pumped storage for energy autonomy – Canary Islands, Spain

The small Spanish volcanic island of El Hierro in the Canary Islands is set to become the first energy-autonomous island in the world. This innovative project was first mooted 30 years ago. A hybrid hydro-wind plant should be completed by the end of 2012. In order to balance the intermittency of wind energy provided by the island's five wind turbines, when demand is low the excess supply of electricity will be used to pump water 700 meters up to reach the top of the volcano crater, that provides a potential 500,000 cubic meters of storage (750 MWh). When there is no wind or when energy demand is too high, water will be released from the crater to generate a maximum of a dozen megawatts. Even though the project cost is USD 87 million, it is expected to save 40,000 barrels of crude oil imported annually (approximately USD 4.5 million at February 2012 prices). Moreover, diffusion of electric vehicles within a few years should allow the 11,000 islanders to become completely self-sufficient for energy.

Sources:http://ec.europa.eu/energy/idae_site/deploy/prj042/prj042_2.html
http://www.nytimes.com/2011/01/20/business/global/20iht-rbogisle.html?_r=1
http://www.huffingtonpost.com/2011/07/05/el-hierro-clean-energy-island_n_890587.html

More recently, advanced energy storage technologies such as compressed air energy storage (CAES) as well as flywheels, superconductors, and batteries have been promoted as a means to reach high penetration of intermittent renewables (Denholm and Hand 2011). For instance, the installation of several new CAES plants have been planned in the US (536 MW and 268 MW) and in Germany (90 MW)[18] in order to deal with the large deployment of wind power and the growing need for minute-scale balancing. Other energy storage technologies are appropriate to address intermittency at other frequencies. (See Johnstone and Haščič 2012 for evidence on innovation in advanced energy storage technologies.)

Energy storage utilities can be both suppliers and consumers of power contingent on resource availability (and price signals). According to Van der Linden (2010), the full capability of wind turbine generators is never realized as some of the wind energy is "spilled" to maintain a smooth delivery profile. The deployment of energy storage technologies would hence allow for an increased capacity utilisation of intermittent plants without threatening security of supply. Ackermann (2005) emphasizes the effect of energy storage technologies on grid requirements for renewable integration purposes. Storage would allow higher capacity factor of transmission lines (i.e. they would be used to higher capacity than is the case currently), and thus reduce the environmental footprint and integration costs of IRP.

The cost of advanced energy storage technologies is often put forward as their main limitation. However, according to Bloomberg New Energy Finance, grid-scale energy storage will be economically viable in the UK by 2020 (BNEF 2012). There have been some simulations on the potential of advanced energy storage technologies to accommodate increased intermittent renewable energy penetration. For instance, Solomon et al. (2011) estimated the energy storage capacity needed to increase penetration of solar photovoltaic power using data from Israel Electric Corporation. It is found that 20% grid penetration of solar PV could be achieved without storage, although 5% of the solar-generated energy would be

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[17] For instance, according to Robinson (1974), the Luddington plant in the US has nearly 1.9 GW capacity and may store up to 15 GWh equivalent of water. It has an upper reservoir of more than 3 km long and nearly 1.5 km wide, and has been built in almost 15 years at a cost of more than $340 million.

[18] According to Platts UDI database (2011).

spilled. Denholm and Hand (2011) provide simulations performed in the US Texas grid with penetration of wind, solar PV and concentrating solar power up to 80%. They emphasize both the limited flexibility of thermal generators and the current inability of the system to trade power with adjacent regions as the primary barriers to the integration of intermittent renewables, resulting in large energy curtailment. They conclude that penetration rates up to 50% with curtailment lower than 10% could be achieved without storage, if and only if, the system is highly flexible (i.e. base-load production tends to zero).

In general these studies imply that advanced energy storage will be needed if countries are to achieve very high penetration of IR energy sources in the future. However, it must be noted that cost-effective alternatives to energy storage are already available to system planners and operators, such as combined heat and power (CHP) units or electric heat pumps with thermal storage reservoirs.[19]

Demand-side management is another remedy to achieve ambitious renewable objectives without putting supply security in jeopardy. Demand for electricity is not perfectly price inelastic in the short-run as "big consumers" of electricity are more and more capable of responding to spot price signals.[20] When large surpluses of intermittent renewable power occur on the market, spot prices are driven down and may even go negative if the market design permits.[21] However, despite this limited form of demand-side management, IR power plants may be forced to spill energy in times of low demand and abundant energy resource, due to the lack of price-sensitivity on the demand side of the market. For that reason, the rigidity of demand is still a fundamental constraint to achieve high penetration of IR in the supply mix.

More advanced demand-side management strategies that would increase price responsiveness of consumers have been the subject of much research recently.[22] This includes the development of smart meters, smart grids, electric cars and so forth.[23] (See Box 4 for a discussion of the possible role of the electric vehicle fleet.) The bottom line is that market prices should internalize real-time resource availability so that consumers, if equipped with adequate technologies, would be provided with the right incentives for consumption. Ambec and Crampes (2012) provide theoretical evidence that in the presence of intermittent renewable sources efficient electricity prices should be contingent on both demand and resource availability.

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[19] See EcoGrid.dk Phase 1 Summary Report (2010), IEA Task 25 (2006).

[20] See Crampes and Léautier (2010) for a theoretical study on "voluntary dispatch contracts" between grid operators and "big consumers".

[21] Nord Pool Spot has implemented negative spot prices as an option in the market-clearing process since October 2009.

[22] See Clastres (2011) for comprehensive information on smart grids.

[23] See MacKay (2008) for an insightful review of those technologies.

Box 4. Using electric car batteries to support the grid

Instead of creating costly storage utilities to specifically cope with renewable energy intermittency, electric vehicles, thanks to their batteries, could be used as energy storage devices, particularly if they are linked to "smart chargers". More precisely, each car would be charged when there is excess supply, and would give energy back to the grid when demand is high. The user could be financially rewarded for the electricity provided back to the grid e.g. with a feed-in-tariff. To be user-friendly, "smarts chargers" would be programmable to ensure the battery is fully charged at a certain time (e.g. 7 a.m. every morning from Monday to Friday) notwithstanding the grid needs. In the case of the United Kingdom, the replacement of the present 30 million petrol-powered cars with an equivalent electric fleet could accommodate 10 GW of wind power, which is the country's average wind delivery power target for 2020 (for a total 30GW wind power capacity). Henceforth, in order to balance generating capacity and storage needs, every 3MW of wind capacity built should ideally be matched with the production of 3000 electric vehicles (MacKay, 2008).

Sources: David JC MacKay (2009) - Sustainable Energy, Without the Hot Air. Available at : *http://www.withouthotair.com/*
http://iea-etsap.org/web/Highlights%20PDF/E18IR_electr_stor_GS_Jan2012_rev3FINAL%20HL.pdf

3.3. Cross-border trade **in** *electricity*

Denmark is a well-known illustration of the use of cross-border electricity trade as a way to achieve high penetration of intermittent renewables. The full integration of Danish grids into the Nordic power market (Nordpool) allows for the use of large domestic wind generation capacity with foreign (and quite distant) pumped storage plants in order to smooth production profiles thank to price mechanisms. From nearly 20% in 2009, Denmark plans to achieve 50% of gross energy consumption generated from wind power by 2025. This could never be feasible without trade in electricity through well-integrated international power markets (see Box 5).

The technical feasibility, and hence the economic viability, of power interconnectors between distant regions (and across seas) have been dramatically improved throughout the last decade. Two illustrative examples are the Basslink submarine cable between Tasmania and Australia (370 km) commissioned in 2005 and the NorNed interconnector (580 km), completed in 2008 at a cost of $600 million, between Norway and Netherlands across the North Sea (the longest submarine power cable in the world). Such an engineering feat gives many autarkical islands the possibility to trade electricity with their neighbours. For instance, a hypothetical power link between Japan's Honshu Island and Korea would not be longer than 400 km, and might be very helpful for an adequate deployment of intermittent renewable technologies and improving energy security in both countries.

There is a wide array of publications on electricity trade in the literature. TradeWind (2009) reports on a simulation of a large-scale cross-border wind power transmission and market design at the European level. In line with EWIS (2010a) and Roques et al. (2010), the analysis emphasizes the importance of cross-border electricity trade to achieve EU renewable targets and corresponding urgent needs for grid reinforcements. Poÿrÿ (2009) analyzes the potential of an interconnection between Ireland and the United Kingdom and concludes that it cannot fully address the challenge associated with the two countries renewable energy targets.

Box 5. Denmark – the challenge of achieving very high penetration of wind power

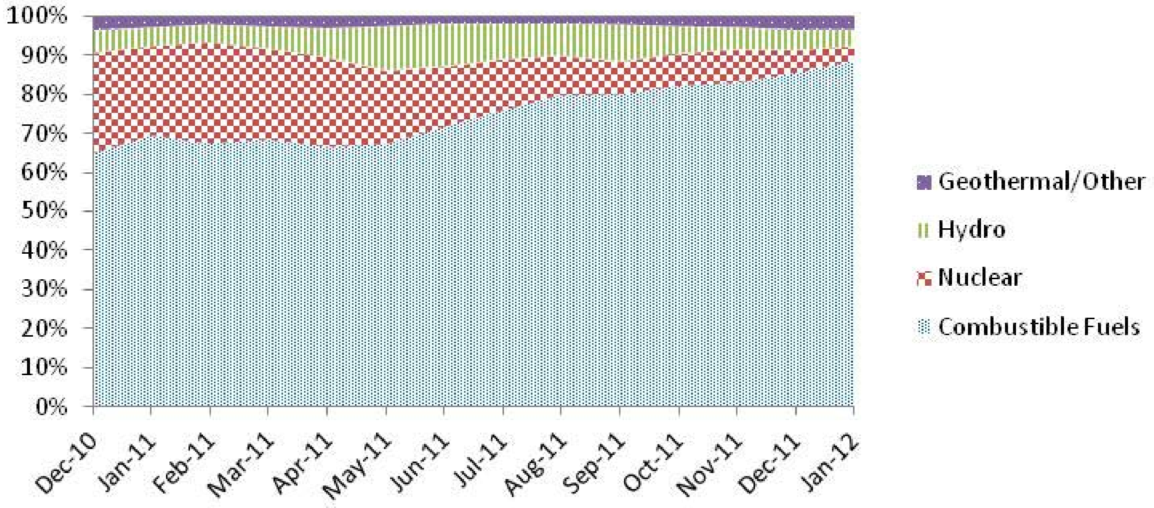
In 2008, nearly 20% of the total electricity consumed in Denmark was generated by Danish wind farms. This has been possible thanks to existing trans-boundary transmission links between Denmark's grids and adjacent countries, which allows for the export of surplus wind power to large pumped storage hydro plants in Nordic countries, in particular Norway and Sweden. Denmark has committed to a 30% renewable energy target for 2025, implying 50% of total annual electricity consumption would have to be generated by wind plants. Such high penetration of wind would necessitate a remarkable balancing capacity to accommodate wind fluctuations. Although numerous studies have considered Norway as a potential "green battery" for a number of European countries, transmitting wind power up to Nordic hydro reservoirs may not be the least-cost solution when targeting very high penetration of wind power in multiple countries. First, cross-border electricity trade comes at a cost in terms of transmission losses. Second, interconnectors have limited transmission capacity which may not allow for higher penetration of wind power both in Denmark and other countries. Third, cost-efficient solutions to enhanced flexibility are to be found domestically thanks to deployment of CHP units for instance. EcoGrid (2010) concludes that international balancing resources are unlikely to be sufficient for Denmark to rely on when heading towards 50% wind power, partly due to the increasing competition with German grids to access Nordic hydro resources. The report proposes a complete redesign of the Danish power system with a strong emphasis on the necessity to set up new strategies for wind power integration.

Sources: IEA Task 25 (2006) – Design and Operation of Power Systems with Large Amounts of Wind Power, first results of IEA collaboration. EcoGrid.dk Phase 1 Summary Report (2010) – Steps towards a Danish Power System with 50% Wind Energy.

Box 6. Nuclear and Renewable Power Challenges in Japan

After the March 2011 earthquake and the following disaster of Fukushima Daiichi, most nuclear power plants in Japan were taken off-line. Nuclear power used to account for 30% of the country's electricity generation. As the Japanese public opinion is opposed to restarting of nuclear reactors, electric utility companies had to compensate with production from their old fossil fuel power plants. With heavy reliance on imports of fossil fuels and binding ecological commitments, the government is now trying to replace nuclear energy with RES rather than with fossil fuels. To achieve this goal, one of the world's most generous feed-in-tariff laws was passed in 2011 after the seism, financially encouraging diffusion of IR energy sources.

Figure 6. Monthly electricity generation by technology in Japan as percentage of total electricity supplied



Source: IEA Monthly Electricity Statistics Archives

However, the integration of IR sources is complicated by the fact that the country's grid is split in two. For historical reasons' eastern Japan's grid runs at 50 Hz, whereas western Japan's runs at 60 Hz. Thanks to frequency changing stations transfer of power between the two grids is possible. However, there are only three of these stations, with a total converting capacity of 1 GW. When the earthquake and tsunami struck Japan in March 2011, 10 GW of nuclear capacity was lost in the East, constraining the possibility for western facilities to supplement the eastern grid. As a consequence, frequent electricity cuts and blackouts happened on a regular basis. This underscores the need for greater grid integration, particularly as IR energy plants are projected to make up a higher proportion of the mix. To tackle this issue, the government announced in 2012 the investment of $1.7 trillion for electricity grid modernization over the next 18 years. According to the "*Innovative Strategy for Energy and the Environment*" prepared by the Energy and Environment Council in late 2012 there will be significant enhancement of inter-regional and intra-regional power grids, facilitating the extensive use of IR power sources.

Sources:
http://www.ecoseed.org/business/asia/article/130-asia/12666-japan-turning-to-smart-grid-technology-after-tsunami-%E2%80%93-zpryme
http://www.washingtonpost.com/world/asia-pacific/renewable-energy-sees-its-chance-in-japans-electricity-market/2011/09/30/gIQAJ1X3AL_story_1.html
http://www.nytimes.com/2011/08/20/business/energy-environment/quake-in-japan-is-causing-a-costly-shift-to-fossil-fuels.html?_r=1&pagewanted=all
http://www.wind-works.org/FeedLaws/Japan/JapanFeed-inTariffPolicyBecomesLaw.html

In conclusion, in the absence of sufficient transmission capacity, grid flexibility and electricity trade OECD countries will not be able to make effective use of the ever-increasing IR plant capacity in which they are currently investing. Plants will lie idle, even when ecological conditions could, in principle, allow for the generation of electricity. In other words, energy will be curtailed because of insufficient grid capability. While the IEA (2011a) considers that output curtailment has had limited impact on plants profitability thus far, energy curtailment is likely to rise with penetration of intermittent renewables, reducing IRP capacity utilisation – and hence their profitability[24] - and the amount of low-carbon power generated, implying that more renewable-generation capacity will be needed to achieve the same objectives.

In an effort to 'force' greater use of available IRP capacity, the EU has implemented a Directive for priority grid connection and access of renewable power plants in 2009, with only security of supply considerations to justify any derogation.[25] Such policies are typically useful to grant security for investment projects in renewable plants, thus to encourage entry of renewable plants. In Germany, priority dispatch for renewable generation has primarily been enforced through the 2004 Renewable Energy Sources Act (EEG), which mandates grid operators to pay compensation to 'green power' suppliers up to 95% of lost income when renewable energy curtailment occurs, and 100% if it lasts beyond a certain period. This policy, if properly enforced, should lead to minimum generation curtailment and maximization of IRP capacity utilisation.

However, this is a rather heavy-handed way to meet penetration objectives.[26] Under such a scheme, suppliers of electricity generated from IR are guaranteed a market for their output. They are not obliged to compete directly in the market with other electricity providers, who must bear the risks associated with their uncertain supply. Therefore, unless complemented with incentives for the development of transmission capacity and grid flexibility (including international trade) priority dispatch will be a costly means of securing the capacity utilisation of IR plants. It is important to assess the necessary investments in grid flexibility and transmission capacity in accordance with renewable policy objectives, and introduce incentives for all agents (plants owners, grid operators) to encourage such investments.

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[24] Although IRP generally receive payments relative to their opportunity cost of not supplying power during curtailment periods. Such payments vary across grids and countries. For example, Xcel Energy's Northern States Power Minnesota (NSP) makes whole kWh payments for both fixed and variable costs (covering the lost value of both production tax credit and energy). In 2008, 23 GWh of wind power were curtailed in NSP (for only 1.3 GW of wind generation capacity installed), resulting in $2.5 million payment to wind facilities (Fink et al. 2009).

[25] According to the European Directive 2009/28/EC, "(c) Member States shall ensure that, […] system operators shall give priority to generating installations using renewable energy sources, […] appropriate grid and market-related operational measures are taken in order to minimise the curtailment of electricity produced from renewable energy sources, […] the responsible system operators report to the competent regulatory authority on [any significant curtailment] measures and indicate which corrective measures they intend to take in order to prevent inappropriate curtailments."

[26] The story is different in the US since power markets are more liberalized than in Europe. Several grid operators, such as ERCOT, have implemented nodal pricing as a means to deal more efficiently with wind power and associated network congestions. Pricing electricity according to its availability at several nodes on the network, rather than pricing it on the entire grid zone, is expected to allow determining the economically efficient energy curtailment and relieve congestions (see Ela 2009).

4. Model, Data and Results

4.1 Theoretical model

The objective of the model is to empirically assess the factors affecting IRP capacity utilisation. The model focuses on wind energy since it is the most widely deployed, variable and unpredictable among intermittent renewables. However, the analysis is of broader relevance to solar photovoltaic and marine power.

Based on the discussion in section 3, and assuming grid operators give priority to renewable energy sources as long as there is sufficient transmission capacity and grid flexibility, we express capacity utilisation at the national level as the effective capacity factor (ECF_t). This is determined for each country, at the national grid level and in each period *t*, by the following model.

$$(E1)\quad ECF_t = f_t(Wind\ Speed_t)(Grid\ Capacity_t)^{\beta_1(\theta_t)}(System\ Flexibility_t)^{\beta_2(TRADE_t,\theta_t)} \quad \forall t$$

where,

$Grid\ Capacity$, as discussed in section 3.1, is reflected in network infrastructures. $System\ Flexibility$, as discussed in section 3.2, reflects the availability of dispatchable power plants and energy storage facilities, with electricity trade as a complement. This model is subject to the following assumptions.

(1) $0 \le ECF_t \le \overline{ECF_t} = f_t(Wind\ Speed_t) \le 1$, with ECF_t being the ratio of total wind power generated relative to installed wind generation capacity at time *t*. $\overline{ECF_t}$ is ECF_t's upper bound given wind speed and technology at time *t*. The former is defined by $Wind\ Speed_t$ while $f_t(.)$ describes the latter. The upper bound may only be achieved in the absence of production constraints, formally if $(Grid\ Capacity_t)^{\beta_1(\theta_t)}(System\ Flexibility_t)^{\beta_2(TRADE_t,\theta_t)}$ is equal to 1. That is if, either $Grid\ Capacity_t = 1$ or $\beta_1 = 0$ and, either $System\ Flexibility_t = 1$ or $\beta_2 = 0$. β_1 and β_2 are the elasticities of *ECF* with respect to $Grid\ Capacity_t$ and $System\ Flexibility_t$, respectively.

(2) $\theta_t = \frac{WCAP_t}{Elec\ Cap_t}$ is the ratio of wind power generation capacity relative to total generation capacity in the grid (considering all technologies) at time t, referred to as "wind capacity penetration". Note that $\theta_t \in (0,1)\ \forall t$.[27] Importantly, this implicitly accounts for the presence of various policy incentives directed at increasing renewable energy capacity.

(3) $f_t'(Wind\ Speed_t) \ge 0$, i.e. capacity utilisation (ECF_t) increases with wind speed ($Wind\ Speed_t$), $\forall t$.

(4) $f_t''(Wind\ Speed_t) \le 0$, i.e. marginal capacity utilisation (ECF_t) decreases with wind speed, $\forall t$.

(5) $0 \le (Grid\ Capacity_t) \le 1$, i.e. grid capacity takes values between 0 and 1. More transmission capacity is available to carry wind power throughout the region as $Grid\ Capacity_t$ gets closer to 1, and vice versa.

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[27] θ_t measures the presence of wind capacity in the power network at time *t*.

(6) $0 \leq (System\ Flexibility_t) \leq 1$, i.e. system flexibility takes values between 0 and 1. More flexibility is available to deal with wind power in the system as $System\ Flexibility_t$ gets closer to 1, and vice versa.

(7) $0 \leq \beta_1(\theta_t) \leq 1$, the elasticity of ECF_t with respect to $Grid\ Capacity_t$ takes values between 0 and 1 (e.g. $\beta_1(\theta_t)$= 0 means that ECF_t is not affected by $Grid\ Capacity_t$).

(8) $\frac{\delta\beta_1(\theta_t)}{\delta\theta_t} \geq 0$, i.e. the elasticity of ECF_t with respect to $Grid\ Capacity_t$ increases with the amount of wind generation capacity on a given network (θ_t), which means that the need for grid capacity grows along with wind generation capacity.

(9) $0 \leq \beta_2(\theta_t, TRADE_t) \leq 1$, i.e. the elasticity of ECF_t with respect to $System\ Flexibility_t$ takes values between 0 and 1. $\beta_2(\theta_t, TRADE_t)$=1 means that ECF_t is dramatically affected by $System\ Flexibility_t$.

(10) $\frac{\delta\beta_2(\theta_t,TRADE_t)}{\delta\theta_t} \geq 0$, i.e. the elasticity of ECF_t with respect to $System\ Flexibility_t$ increases with the amount of wind generation capacity in grids, meaning the larger wind generation capacity is the greater will be the need for system flexibility (because of larger variability and uncertainty on the supply side).

(11) $\frac{\delta\beta_2(\theta_t,TRADE_t)}{\delta TRADE_t} \leq 0$, i.e. the elasticity of *ECF* with respect to $System\ Flexibility_t$ decreases with the magnitude of cross-border electricity trade $(TRADE_t)$. This condition is equivalent to assuming that enhanced electricity trade with adjacent regions reduces domestic requirements in terms of system flexibility for dealing with a given amount of intermittent renewable power generation.

4.2 Empirical model and data

The primary goal of this research being to estimate the empirical effect of each "strategy" on average wind capacity utilisation as installed generation capacity increases, the following four models are specified.[28]

$$(E2)\ \ ECF_{it} = \beta_0 + \beta_1 WS_{it} + \sum_{p=1}^{4} \beta_{p2} DISP_{pit} + \beta_3 GRID_{it} + \beta_4 TRADE_{it} + \beta_5 STOR_{it} + \alpha_i + \varepsilon_{it}$$

$$(E3)\ \ ECF_{it} = \beta_0 + \beta_1 WS_{it} + \beta_2 DISP_{it} + \sum_{p=1}^{4} \beta_{p3} GRID_{pit} + \beta_4 TRADE_{it} + \beta_5 STOR_{it} + \alpha_i + \varepsilon_{it}$$

$$(E4)\ \ ECF_{it} = \beta_0 + \beta_1 WS_{it} + \beta_2 DISP_{it} + \beta_3 GRID_{it} + \sum_{p=1}^{4} \beta_{p4} TRADE_{pit} + \beta_5 STOR_{it} + \alpha_i + \varepsilon_{it}$$

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[28] It must be however noted that it is not directly derived from the theoretical model presented in Section 4.1 for estimation purposes.

$$(E5)\ ECF_{it} = \beta_0 + \beta_1 WS_{it} + \beta_2 DISP_{it} + \beta_3 GRID_{it} + \beta_4 TRADE_{it} + \sum_{p=1}^{4} \beta_{p5} STOR_{pit} + \alpha_i + \varepsilon_{it}$$

Equations (E2) to (E5) describe linear relationships between the dependent variable ECF_{it}, the "effective" capacity factor, and the explanatory variables. Those include average wind speed (WS_{it}), dispatchable generation $(DISP_{it})$, grid transmission capacity $(GRID_{it})$, cross-border electricity trade $(TRADE_{it})$, and energy storage $(STOR_{it})$ where $t = (1990, \dots, 2009)$ indexes time and $i = (1, \dots, 31)$ indexes the country (cross-sectional unit).[29] Fixed effects (α_i) are introduced to control for unobserved cross-country heterogeneity. The error term (ε_{it}) captures all residual variation. As noted above, the relative importance of these different factors is likely to vary with the level of wind capacity penetration. In order to account for such interactions, explanatory variables have been interacted with binary variables reflecting the share of wind power generation capacity relative to total electric generation capacity in a country in a given year (referred to as "wind capacity penetration" in this paper). Thresholds respectively equal to the 25th, 50th and 75th percentiles of wind capacity penetration ($WCPEN_{it}$) are defined to generate four dummy variables of equivalent number of observations. Dummies are then interacted with each explanatory variable in order to generate sixteen additional variables, formally $DISP_{pit}$, $GRID_{pit}$, $TRADE_{pit}$ and $STOR_{pit}$ $\forall p \in \{1,2,3,4\}$ where *p* denotes the corresponding group unit for penetration of intermittent renewables in country *i* in year *t* . Group 1 contains observations with the lowest values for wind capacity penetration, while Group 4 contains the highest.[30] Each of the four models (E2) (E3) (E4) and (E5) includes only one explanatory variable interacted with dummies. Models are separately estimated in order to avoid collinearity problems arising from the inclusion of all dummy-interacted variables in a single equation.

The dependent variable having been presented in Section 2 let us now describe each of the explanatory variables. The capacity utilisation of wind farms should primarily be affected by wind speed. As wind blows stronger over the course of a year, wind plants have the potential to generate more electricity, and vice versa. The model presented in this paper considers annual data by country; a value for wind intensity WS_{it} has been assigned to each country *i* for each year *t* in the period 1990-2009. The wind speed variable (*WS*) used here is constructed as the annual average wind speed at production sites weighted by each turbine's nameplate capacity, expressed in meters per second (m/s). *WS* is expected to have a positive effect on *ECF*.

The annual average wind speed in country *i* at year *t* (WS_{it}) is computed based on spatially disaggregated data. Historical monthly mean wind speed data were first extracted from NCEP/NCAR Reanalysis 1 dataset[31] that contains monthly mean wind speed at 10 meters above ground for 10368 rectangles of 2.5° latitude by 2.5° longitude covering the entire world. This data set is widely used for wind resource assessments.[32] We computed the corresponding annual mean wind speed for 4404 wind farms in

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[29] All OECD countries have been included in the analysis, except those that had no wind-generation installed capacity during the period 1990-2009 (Iceland and Slovenia), or for statistical reasons (Luxembourg).

[30] Table 2a and 2b in section 4.3 show descriptive statistics of the constructed dummies with respect to wind capacity penetration levels when considering different samples of countries.

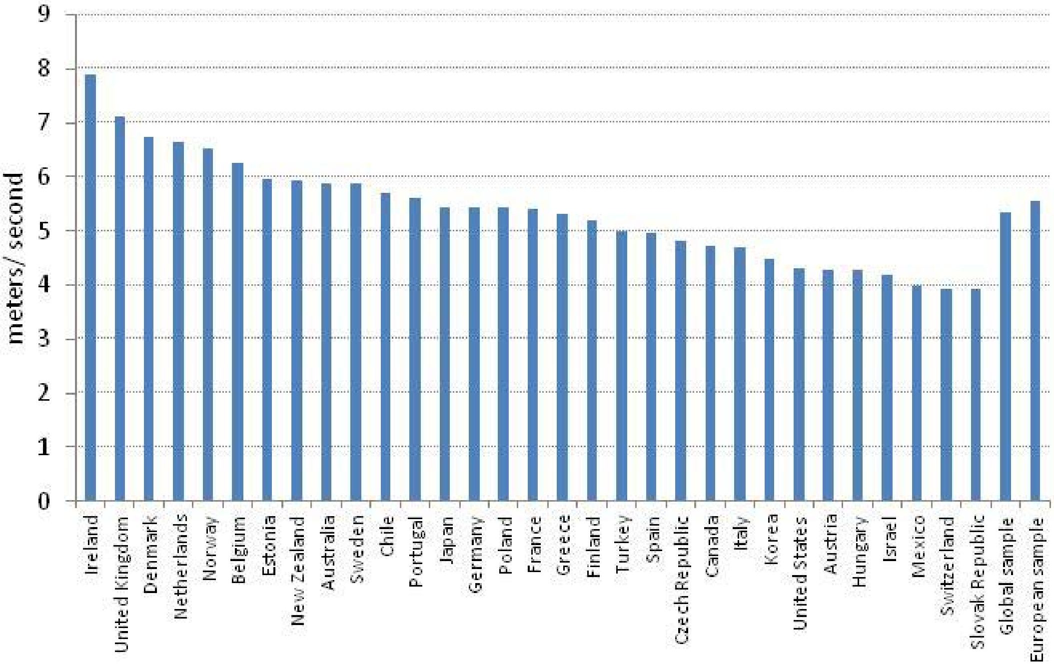
[31] Available at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html

[32] According to the *Wind Resource Assessment Handbook (2010)*, this is the most widely used data set for wind resource assessment. The book presents descriptive statistics, analysis and substantial critics of different wind-related data sets.

OECD countries geolocated using the Platts UDI database[33] and an online geocoder.[34] Coordinates for operational plants from 1990 to 2009, while have been matched with the nearest coordinates in the annual wind speed data in the NCEP/NCAR database.

More precisely, annual average wind speed in each country was calculated as average of annual wind speed at each wind plant location. This was then weighted by installed generation capacity at that site relative to total capacity in the country. This provides a good measure of the potential annual wind energy flow that may have been used as an input for wind power generation in a country. There are however shortcomings with the data. The dimension of wind speed data is quite low, and it contains values at 10 meters above ground, which is below usual hub heights. Furthermore, for some countries weighted average wind speeds do not account for all wind turbines installed at the time because of missing information concerning their locations. Calculations generally include wind farms representing 75% to 100% of installed capacity at the time, though coverage can be as low as 30% in a few cases (for the U.S. mostly).[35] Figure 7 below shows long-term annual average wind speed at wind production sites for 31 OECD countries (for observations included in the final sample). It may be noticed that annual average wind speed at turbine sites tends to be larger in European countries.

Figure 7. Long-term Average Wind Speed at Generation Sites



As noted above, dispatchable generation (*DISP*) is another factor that may determine *ECF*. Dispatchable power plants[36] are those capable of promptly ramping output up and down on demand at reasonable costs. They introduce flexibility on the supply side and, as such, contribute to intermittent

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[33] The Platts UDI database contains comprehensive information on wind turbines commissioning and retirement years as well as generation capacity and location by city and country.

[34] Available at http://www.gpsvisualizer.com/geocoder/

[35] See Annex 1 for corroboration of the relationship between wind speed and *ECU*.

[36] In this study, dispatchable power plants only refer to those fed with water or gas, since they constitute the bulk of that plant type. This does not include pumped storage plants which are accounted for in a separate variable.

renewables grid integration. More specifically, if a country is able to 'ramp down' a significant share of its generating capacity, it will be able to make better use of its IRP capacity. The availability of dispatchable power is expected to have a positive impact upon. We consider that if a larger share of a country's annual load is generated from dispatchable sources, system flexibility is greater[37] and intermittent renewables possibly will produce more.[38]

The variable $DISP_{it}$ is included as a proxy for country *i*'s capability to complement wind power with dispatchable power in year *t*. It is computed as the annual amount of power generated from gas-fired and hydro plants in GWh normalized by annual demand for electricity, which is the sum of annual power exports and domestic consumption in GWh.

Transmission capacity may also explain *ECF*. The variable $GRID_{it}$ has been included as a proxy of grid quality for country *i* in year *t*. It is constructed as the length of installed transmission lines with voltages at least equal to 330 kV, normalized by the sum of electricity imports and total domestic electricity production in GWh. $GRID_{it}$ is hence a ratio expressed in km/GWh, which provides a measure of the available transmission capacity per unit of output transmitted through a country's network in a given year. We consider that a grid is more resilient if there is more high-voltage transmission lines (HVTL) for a given annual power flow, due to both additional lines and replacement of lower voltage ones, such as 220 kV for instance. This variable may further capture the spatial dispersion of a country's grid, since HVTL are typically needed to transmit electricity across long distances. This means that an increased value of *GRID* might imply that the network covers a larger spatial area, and would thereby have greater potential to spread intermittent renewable plants within national boundaries.

The overall effect of *GRID* on *ECF* is expected to be positive. On the one hand, the integration of intermittent renewables into the system is made easier since transmission capacity is enhanced for a given amount of power passing through the network. Recent studies anticipate the lack of transmission capacity to become a crucial barrier to wind power integration as penetration of wind energy rises.[39] We may therefore expect the impact of *GRID* on *ECF* to be more important when intermittent renewables penetration reaches higher levels. On the other hand, the transmission network may be spread over a larger territory as *GRID* increases, which allows for a potentially larger spatial dispersion of intermittent renewables and thus reduce their aggregated variability. One may consider that countries with large wind energy deployment have already taken advantage of geographic dissemination of their intermittent renewable plants.[40] This secondary effect would likely be more significant at low penetration rates of wind power.

The reason to focus on lines with voltage higher than 330 kV is two-fold. It is generally reckoned that the lower the voltage the weaker the system. HV transmission lines, such as 400 kV lines, allow for carrying large amounts of power with reduced transmission losses and improved voltage regulation. Therefore, accounting for HV lines provides a rough assessment of a grid's capability to integrate intermittent renewable power. It should be noted that HV transmission lines constitute the backbone of a country's grid, typically used for power transportation throughout the national territory, and beyond thanks to interconnectors. Transmission lines with lower voltage, such as 220 kV, are less relevant for this analysis. For instance in Germany, 220 kV transmission lines spanned over 22,873 km in 1994, and slowly went down to 15,232 km in 2009. On the contrary the total length of 400 kV lines was 17,482 km in 1994,

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[37] According to Ackermann et al. (2009) for instance, the predominance of hydro-based generation in the New Zealand power system provides an inherent flexibility to deal with the variability of wind energy.

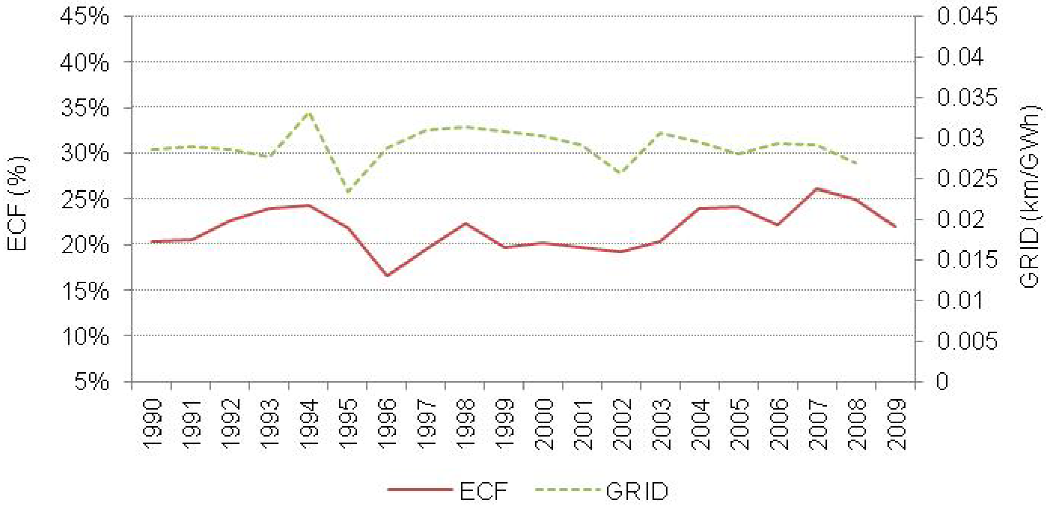
[38] Assuming a lack of dispatchable generation was a significant barrier for wind plants production.

[39] See Ackermann et al. (2009), Rogers et al. (2010), Ela (2009), Fink et al. (2009).

[40] This may not be entirely true, see Drake and Hubacek (2007) for an illustration in the UK.

and 20,213 km in 2009.[41] Figure 8 below shows the relationship between *ECF* and *GRID* for Denmark through time and shows that there is a positive correlation (0.2711) between the two series. Drought stroke Norway during summer 1996. As a result, Denmark exported large amounts of power in order to compensate water shortage in Norwegian dams. One may argue this has increased congestions on the domestic (and trans-boundary) network which might have reduced wind plants capacity utilisation to some extent. Note also that average wind speed was lower in 1996 than in 1995 (See Annex 1).

Figure 8. ECF and GRID for Denmark



Source: ENTSO-E, ABS, OECD (2011).

Different data sources were used to calculate the variable *GRID*. ENTSO-E data on transmission lines have been used for the period 1994 to 2009 for continental Europe.[42] Data obtained from ABS Energy Research and the NRG Expert's Transmission and Distribution Database were used to generate data for continental Europe prior to 1994 and for other OECD countries for all years. This was generated as follows: data on total length of transmission lines on a five-yearly basis were obtained from ABS Energy Research. Data for intervening years were interpolated linearly to reduce the number of missing observations. A disaggregation of ABS data by voltage level was performed by using the shares of transmission lines of more than 330 kV for each country of interest, based on values in the NRG Expert's Transmission & Distribution database.

Energy storage is another potential strategy to increase system flexibility. $STOR_{it}$ is a measure of the extent of energy storage in country i's grid at year t. It is constructed as the ratio between electricity production from pumped storage hydro plants and the sum of domestic electricity generation and power imports. As *STOR* rises, energy storage is used to a larger extent and may facilitate the integration of intermittent power. This variable is thus expected to have a positive effect on *ECF*. We focus on pumped storage as it used to be the only energy storage technology deployed, and even in current practice deployment of advanced energy storage technologies remains limited. Furthermore, no time-series data

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[41] Data were extracted from ENTSO-E data portal at https://www.entsoe.eu/resources/data-portal/

[42] Those countries are Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden and Switzerland. Some values were corrected thanks to additional information directly collected from Danish, Hungarian and Austrian transmission system operators (acknowledgment to Tamas Medovarszki).

were found on volumes of electricity generated or installed generation capacity for such advanced technologies.[43]

Cross-border electricity trade may also affect *ECF*. $TRADE_{it}$ is an index of the extent of electricity trade in country *i* in year *t*. It has been constructed as the sum of electricity imports and exports, normalized by the sum of electricity imports and domestic production. It is an approximation for a country's actual use of electricity trade with respect to the size of the domestic electricity market.

Adding up power exports and imports helps to eliminate some idiosyncrasies[44] and provides a broader picture of the development of electricity trade. The impact of electricity trade on capacity utilisation of intermittent plants is two-fold. Electricity imports may serve as a potential source of 'dispatchable power' for balancing supply fluctuations, and as such, contribute to meet power system flexibility requirements for adequate wind power integration. Whereas exporting electricity may contribute to smoothing domestic supply of intermittent renewable power over time without curtailing output, consequently reducing those flexibility requirements. The effect of cross-border electricity trade on the capacity utilisation of wind plants is expected to be positive. However, it is also expected to vary with the penetration of intermittent renewables. As more variable power enters the network, electricity trade may provide one key option to deal with increased variability (and uncertainty) on the supply side of the system without limiting intermittent renewables plants capacity utilisation.

And finally, a variable reflecting the penetration of wind power generation capacity ($WCPEN_{it}$), is included. This accounts for the difficulty of ensuring effective capacity factors as the capacity of wind power increases relative to total power capacity. As explained above, this variable is interactive with other explanatory variables.

Descriptive statistics for the dependent and explanatory variables are shown in Table 1. Mean effective capacity factor is slightly higher in the global sample of 31 OECD countries than in the subsample of 21 European countries. Discrepancies may also be noted for the explanatory variables, e.g. cross-border electricity trade is on average more important in Europe. Tables 2 and 3 detail the dummy variables designed for taking account of varying penetration rates of wind power.

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[43] We tried to overcome the lack of data for advanced energy storage installed capacity by considering protection as a proxy for diffusion, i.e. using patent data to measure (current and future) installed capacity. Patent data from 1960 to 2010 were extracted from the PATSTAT database by application office, and used to build a proxy for advanced energy storage installed capacity. However, interpretation of such variable is difficult because advanced energy storage utilities have likely had no effect on wind farms capacity utilisation in practice so far. Moreover, collinearity problems arose from the inclusion of this variable.

[44] There is typically a negative correlation between the amounts of power imported and exported, although for most countries the total quantity exchanged tends to increase over the last two decades.

Table 1. Descriptive statistics for the dependent and explanatory variables

Variable	Unit	Obs	Mean	SD	Min	Max
Effective Capacity Factor *ECF* (%)	Wind power prod / Wind theoretical capacity	444 (323)	20.6% (19.74%)	7.051% (6.062%)	6.715% (6.715%)	48.72% (48.72%)
Wind Speed WS (m/s)	Annual weighted average at country levels	443 (322)	5.449 (5.746)	1.105 (1.075)	2.657 (3.330)	9.833 (9.833)
Wind Cap penetration WCPEN (%)	Wind capacity / Total generation capacity	444 (323)	2.401% (3.091%)	4.806% (5.451%)	.0001% (.0001%)	25.99% (25.99%)
Dispatchable Generation DISP (%)	Dispatchable power prod / Total available power	444 (323)	34.60% (31.78%)	22.25% (21.15%)	1.92% (1.92%)	98.75% (98.75%)
Transmission Capacity GRID (km/GWh)	Kilometers of HV lines / Total available power	444 (323)	.0388 (.0347)	.0233 (.0190)	.0091 (.0091)	.1154 (.1032)
Electricity Trade TRADE (%)	Power exchanged / Total available power	444 (323)	15.78% (20.92%)	16.16% (16.05%)	0 (0)	76.20% (76.20%)
Energy Storage STOR (%)	Pumped Hydro power prod / Total available power	444 (323)	0.669% (0.804%)	0.689% (0.734%)	0% (0)	3.905% (3.905%)

Notes: Values corresponding to the European sample are in parentheses.

Table 2. Descriptive statistics for Wind Capacity Penetration (WCPEN) dummies

Sample	Dummy n°	Distribution	Obs	WCPEN's Lower bound	WCPEN's Upper bound
Europe (21 countries)	1	0% - 25%	80	0 %	.0908 %
1990-2009	2	25% - 50%	80	.0908 %	.6197 %
	3	50% - 75%	81	.6197 %	3.209%
	4	75% - 100%	81	3.209%	25.99 %
Global (31 countries)	1	0% - 25%	110	0 %	.0628 %
1990-2009	2	25% - 50%	111	.0628 %	.4274 %
	3	50% - 75%	111	.4274 %	2.071 %
	4	75% - 100%	111	2.071 %	25.99 %

Table 3. Descriptive statistics for Wind Capacity Penetration (WCPEN) dummies

Dummy n°	European Sample
1	Austria(1995); Belgium(1991-2000); Finland(1992-1997); France(1993–2001); Germany(1990); Greece(1990-1991); Hungary(2001-2004); Italy(1990,1991,1996); Norway(1995-2001); Poland(1998-2001); Portugal(1990-1995); Slovak Republic (2003-2009); Spain (1992-1993); Sweden (1990-1993); Switzerland(1997-2008); United Kingdom(1990-1992)
2	Austria (1997-2000); Belgium (2001-2004); Czech Republic(2004-2006); Finland (1998-2006); France (2002-2004); Germany(1991-1994); Greece(1993-1998); Hungary(2005-2006); Ireland(1992-1996); Italy(1997-2000); Netherlands(1990-1992); Norway(2002-2004); Poland(2002-2006); Portugal (1993-1999); Spain (1994-1996); Sweden (1994-2000); Switzerland(2009); United Kingdom(1993-2001)
3	Austria (2002-2004); Belgium (2005-2008); Czech Republic(2007-2009); Finland (2007-2009); France (2005-2008); Germany(1995-1998); Greece(1999-2003); Hungary(2007-2009); Ireland(1997-2002); Italy(2001-2007); Netherlands(1993-1999); Norway(2005-2009); Poland(2007-2009); Portugal (2000-2003); Spain (1997-1999); Sweden (2001-2008); United Kingdom(2002-2007)
4	Austria (2005-2009); Belgium (2009); Denmark(1990-2009); Estonia(2009); France(2009); Germany(1999-2009); Greece(2004-2009); Ireland(2003-2009); Italy(2008-2009); Netherlands(2003-2009); Portugal (2004-2009); Spain (2000-2009); Sweden (2009); United Kingdom(2008-2009)

4.3 Results and discussion

All models are estimated separately for the global sample of 31 OECD countries and a subset of 21 European countries, with country fixed effects. The estimation results are displayed in Table 4 and Table 5.

Findings confirm that, although *ECF* mostly depends on ecological factors (i.e. annual average wind speed in the country) it is also significantly affected by other explanatory variables that are subject to policy incentives. The estimated results suggest that, as expected, dispatchable generation and transmission capacity have a positive and statistically significant effect on *ECF*. This underlines the importance of strong and flexible domestic grids to ensure maximum use of IRP. Similarly, the effect of energy storage is estimated positive and statistically significant, except at very low penetration rates of wind generation capacity. Dispatchable plants may be a sufficient flexible resource to deal efficiently with intermittency at low penetration levels. The impact of cross-border electricity trade, however, is only found to be positive and statistically significant for highest penetration levels of wind power in the European sample. International power markets may only be considered as useful for IR capacity utilisation at levels of penetration which are relatively high by current standards. However, with increasing penetration rates this threshold will soon be exceeded by a majority of OECD countries.

The impact of grid transmission capacity is estimated to be of greater magnitude than dispatchable generation. This result might support the intuition that the lack of transmission capacity is the primary constraint to integration of output from wind power plants in the grid. To a lesser extent, inadequate flexibility of the systems, such as insufficient ramping capabilities and large minimum load requirement, may also be a limiting factor for intermittent renewable generators. Surprisingly, the estimated effects of dispatchable generation and transmission capacity are approximately constant with penetration rates. The effect of storage is much less important, and only becomes significant with higher penetration rates.

The marginal effect of cross-border electricity trade on *ECF* is estimated to be significantly lower than those of dispatchable generation and transmission capacity. This result may be explained by the importance of the domestic grid's flexibility and transmission capacity for a successful integration of IRP in the first place, irrespective of penetration level. The influence of electricity trade on *ECF* is found to be of greater magnitude and significance for European countries. This was expected given the extent of cross-border electricity trade in Europe and the deployment of wind technologies.

Table 4. Estimation results (Average marginal effects)

	European sample (subset of 21 OECD countries)			*Global sample (31 OECD countries)*		
Model	(E2)	(E3)	(E4)	(E2)	(E3)	(E4)
Interacted variable	DISP	GRID	TRADE	DISP	GRID	TRADE
WS	.8648*** (0.000)	.8125*** (0.000)	.8630*** (0.002)	.6775*** (0.001)	.6245*** (0.001)	.7349*** (0.000)
WCPEN						
DISP		.2614*** (0.001)	.2328** (0.000)		.2853*** (0.000)	.2751*** (0.000)
GRID	.4004*** (0.000)		.4112*** (0.000)	.3903*** (0.000)		.4075*** (0.000)
TRADE	.1447** (0.044)	.1190* (0.095)		.0627 (0.268)	.0731 (0.183)	
STOR	.1433*** (0.001)	.1718*** (0.000)	.1297*** (0.003)	.1095*** (0.004)	.1354*** (0.000)	.1110*** (0.007)
DISP 1	.0506*** (0.002)			.0775*** (0.002)		
DISP 2	.0640*** (0.000)			.0944*** (0.000)		
DISP 3	.0806*** (0.000)			.0611*** (0.000)		
DISP 4	.0602*** (0.000)			.0434*** (0.000)		
GRID 1		.1091*** (0.002)			.1547*** (0.001)	
GRID 2		.1249*** (0.000)			.1575*** (0.000)	
GRID 3		.1138*** (0.000)			.0767*** (0.000)	
GRID 4		.1100*** (0.000)			.0620*** (0.000)	
TRADE 1			-.0215 (0.691)			-.0549 (0.452)
TRADE 2			.0141 (0.423)			.0131 (0.364)
TRADE 3			.0254 (0.107)			.0057 (0.567)
TRADE 4			.0326** (0.049)			.0166 (0.130)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Obs	322	322	322	443	443	443
R^2 within	.1498	.1778	.1738	.1042	.1183	.1271
R^2 between	.0930	.0944	.2907	.0921	.0565	.1963
R^2 overall	.0687	.0732	.1757	.0606	.0456	.1233
(Prob>F)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

*Notes: *, ** and *** respectively refer to 10%, 5% and 1% level of statistical significance. P-values are in parentheses. The dependent variable is effective capacity factor of wind plants. Estimation has also been performed with robust standard errors and no significant difference was noted.*

Table 5. Estimation results (Average marginal effects)

	European sample	*Global sample*
Model	(E5)	(E5)
Interacted variable	STOR	STOR
WS	.9526*** (0.000)	.7913*** (0.000)
DISP	.2156*** (0.000)	.2499*** (0.000)
GRID	.4489*** (0.000)	.4154*** (0.000)
TRADE	.1259* (0.070)	.0538 (0.346)
STOR 1	.0136 (0.455)	.0001 (0.993)
STOR 2	.0441*** (0.000)	.0390*** (0.001)
STOR 3	.0422*** (0.000)	.0243*** (0.000)
STOR 4	.0391*** (0.000)	.0203*** (0.000)
Fixed Effect	Yes	Yes
Obs	322	443
R^2 within	.1998	.1438
R^2 between	.1693	.1414
R^2 overall	.1305	.1001
(Prob>F)	(0.000)	(0.000)

*Notes: *, ** and *** respectively refer to 10%, 5% and 1% level of statistical significance. P-values are in parentheses. The dependent variable is effective capacity factor of wind plants. Estimation has also been performed with robust standard errors and no significant difference was noted.*

Another interesting difference is the larger estimated influence of wind speed on plant capacity utilisation in Europe. This might be explained by two factors. First, wind resource is measured as an annual average over entire countries, and as such, might have a greater explanatory power for smaller countries. More important, European Union countries must ensure that IR electricity generators are given priority access and dispatch[45], and as such, may have higher correlation between effective use of wind plants and wind speed. This is typically true for countries with enforced purchase and transmission obligations such as Germany (see Annex 1). Indeed, in such cases – a small number of observations in the sample – *ECF* will be primarily a function of wind speed.

For ease of interpretation the estimated average marginal effects of the 'interacted' variables for the four different models are presented graphically in Figure 9. These estimated effects are in line with ex ante expectations.

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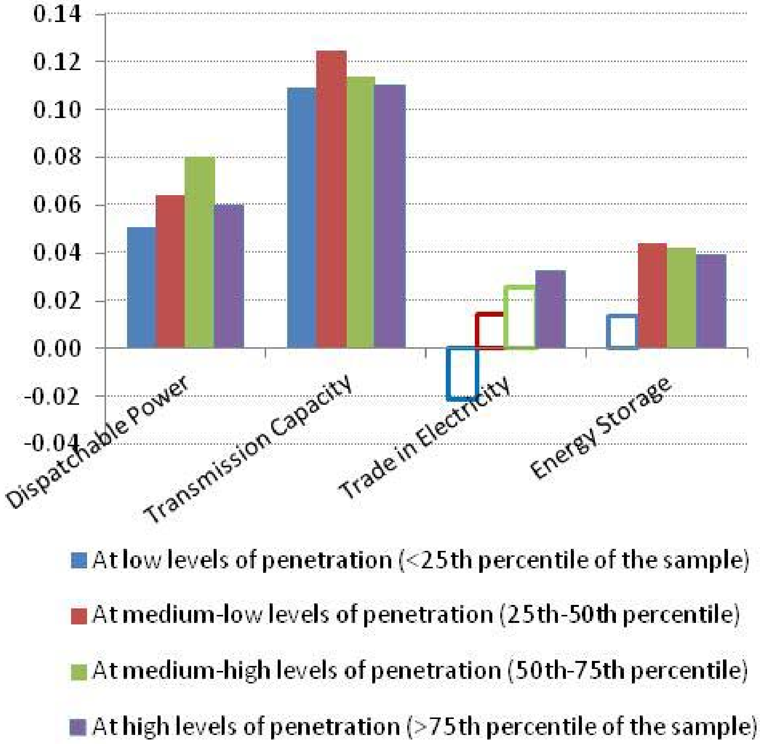
[45] See European Directive 2009/28/EC. It must however be noted that mandated purchase of energy from RES is not implemented in all EU countries (See Eclareon 2011).

Figure 9. Average Marginal Effects of the Strategy Variables at Different Levels of Penetration



5. Simulation of the Effects of Grid Quality on Capacity Utilisation

In this section we propose a simulation that highlights the growing importance of grid infrastructures to meet renewables objectives. With a particular focus on 21 European countries, this simulation is drawn on estimates from model (E3) and calibrated with relevant data from the International Energy Agency's World Energy Outlook 2011 and ABS Energy Research's Transmission & Distribution database. The constant average annual growth rate for total electricity generation in the European Union under the "New Policies Scenario" (WEO 2011) is used to project electricity generation by country towards 2020. Annual targets for the share of installed wind generation capacity relative to total generation capacity (i.e. wind capacity penetration) are imposed at the EU level using data from the "New Policies Scenario". National objectives are set accordingly with EU targets and current domestic wind generation capacity levels.

Average capacity utilisation of wind plants is first estimated at the country level with respect to all relevant factors. Predicted values are then used to derive annual shares of wind power production relative to total electricity generation at national levels, given the projections of installed wind generation capacity. Those shares are finally aggregated at the EU level with respect to national electricity generation volumes. The 'Baseline Scenario' assumes grid transmission capacity increases accordingly with ABS Energy Research forecasts. The 'Grid Expansion Scenario' considers transmission capacities to linearly increase from baseline values in 2009 to values 25% greater than baseline in 2020. On the opposite, they are assumed to decrease from baseline in 2009 to values 25% lower than baseline in 2020 in the 'Grid Shortage Scenario'.

Several other variables are necessary to predict average wind plants capacity utilisation at national levels. All of them are assumed to grow along with domestic electricity generation, with the exception of annual average wind speed which is computed as an average of monthly mean wind speed at production sites over the past 10 years. This average wind speed is kept constant over the entire time horizon of the simulation. Since offshore wind farms have higher capacity factors than onshore wind farms, the model assumes the capacity utilisation of wind plants should evolve along with the share of offshore wind capacity. This is done by applying the growth rate of the weighted average capacity factor – average capacity factor between onshore and offshore wind farms weighted by the respective share of each technology, implicitly assumed in the World Energy Outlook 2011, to predicted values of effective wind plants capacity utilisation. Furthermore, the average capital cost of a MW of wind capacity is computed as an average of the costs of offshore and onshore wind capacity weighted by the respective presence of each technology.

Figure 10 graphs predicted average wind plant capacity utilisation over time at the EU level for the three scenarios. Note that grid transmission capacity is the only variable that varies across scenarios. It appears that average wind plant capacity utilisation in the EU may be up by nearly 25% if domestic grids are well-reinforced than if they are poorly refurbished.

Figure 10. Simulation of Average ECF in the European Union under Different Assumptions of Grid Quality[46]

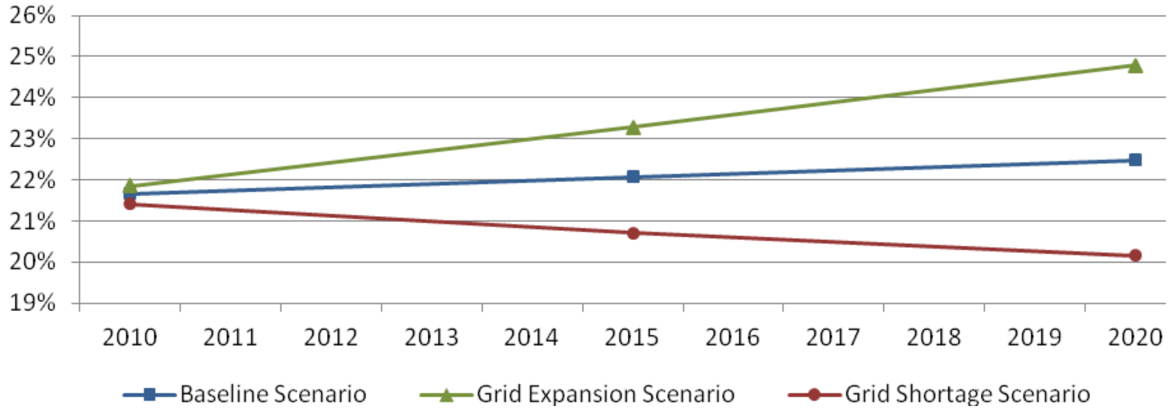


Figure 11 displays shares of wind power generated relative to total electricity generation within the EU for the three scenarios (corresponding values under the New Policies Scenario, for the EU in the WEO 2011, are also added for an indicative purpose). Note that overall wind generation capacity in the EU is constant across scenarios and corresponds to that of the New Policies Scenario of the WEO. Discrepancies across scenarios enlarge as wind generation capacity increases. We find that, in 2020, a total of 200 GW of wind generation capacity installed in European countries (including onshore and offshore turbines) may lead to significantly larger volumes of wind power if domestic grids are effectively reinforced.

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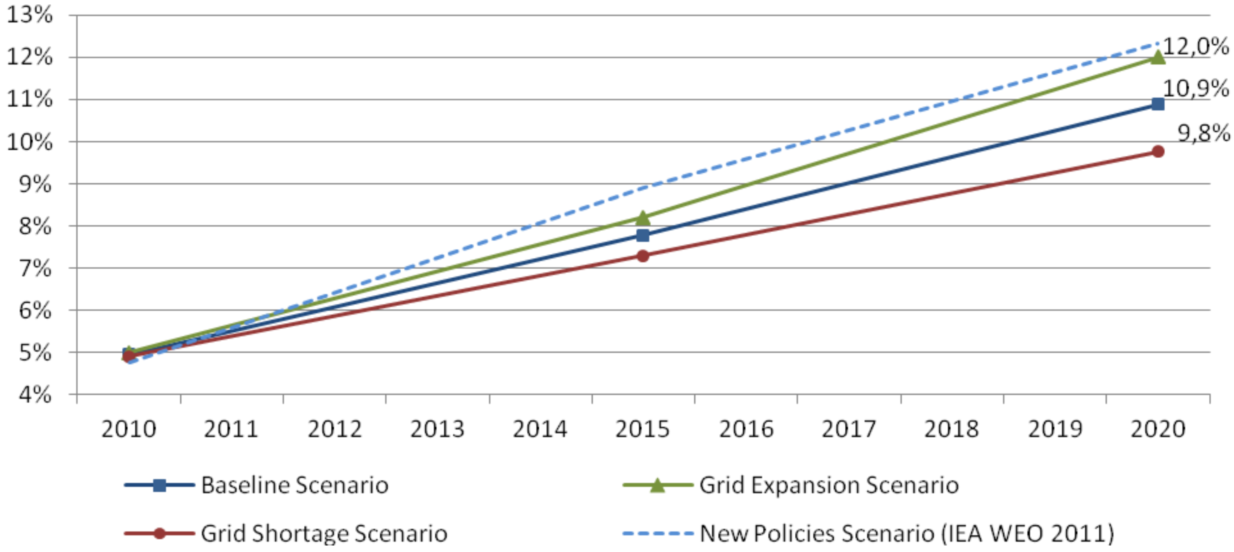
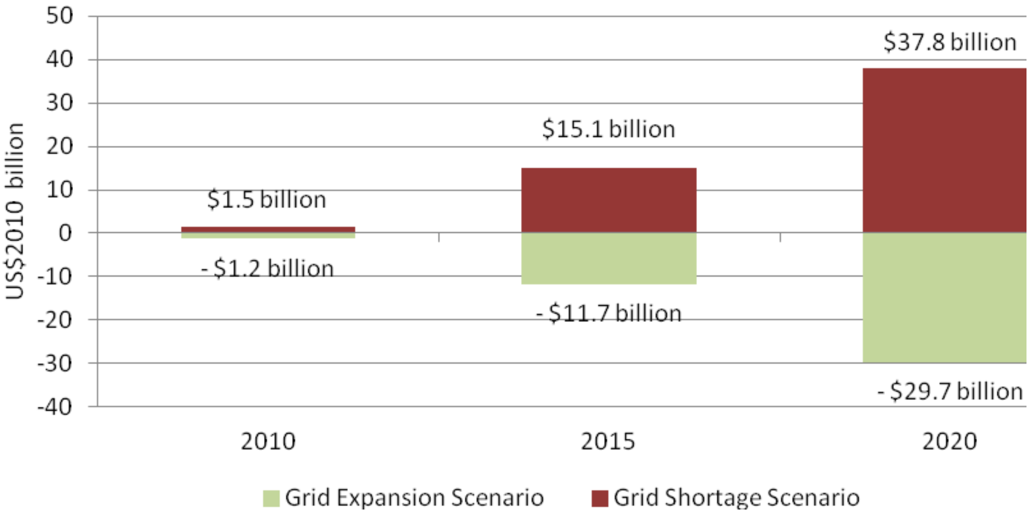
[46] Note that values for ECF in 2020 are lower than those forecast by the European Wind Energy Association ("Pure Power Report"). However, the result of interest is the % difference in *ECF* under different assumptions of grid quality, and not the level per se.

Figure 11. Share of Wind Power relative to Total Power Generated within the European Union



Adequately developed domestic grids may therefore allow for a lower installed wind generation capacity to achieve the same renewables objectives. Figure 12 shows the relative cost of meeting baseline share of wind power under each of the two alternative scenarios, in terms of additional capital invested in wind turbines. The total monetary value of wind turbines required to reach a 10.9% share of wind power at the EU level would be almost $38 billion greater if domestic grids are to be poorly refurbished. Notice that this estimate considers the additional investment in wind turbines required to reach the EU target assuming it would be technically feasible without reducing average wind plants capacity utilisation, which is not a plausible assumption. Similar conclusions (and graphs) are drawn for the case of cross-border electricity trade in the next section.

Figure 12. Relative additional cost of meeting renewables objectives within the European Union



6. Simulation of the Effects of Cross-Border Electricity Trade

Following the same methodology to that detailed in Section 5, this part of the study is aimed at shedding light on the increasing relevance of cross-border electricity trade to meet renewable objectives. A simulation is drawn on estimates from Section 4 and relevant data from the IEA's World Energy Outlook 2011 in order to assess the effect of European power markets when going towards 2020. The "Baseline Scenario" assumes electricity trade to grow along with electricity generation. While the "Autarky Scenario" considers trade to linearly phase out until 2020, the opposite trend is considered in the "Trade Enhancement Scenario". Although the extent of electricity trade is assumed to double in Europe in the latter scenario, it is not the case at country levels. Instead, it increases by a fixed amount equals to the weighted average of the variable TRADE at the EU level in the Baseline Scenario.

Figures 13 to 15 show results from the simulation under different assumptions concerning international trade in electricity. It should be noted that electricity trade will become an increasingly important strategy to meet renewable objectives. The relative additional costs of meeting renewable objectives under each scenario are computed as the additional investment in wind projects required to reach the Baseline Scenario's wind power penetration targets.

Figure 13. Average Effective Capacity Factor in the European Union

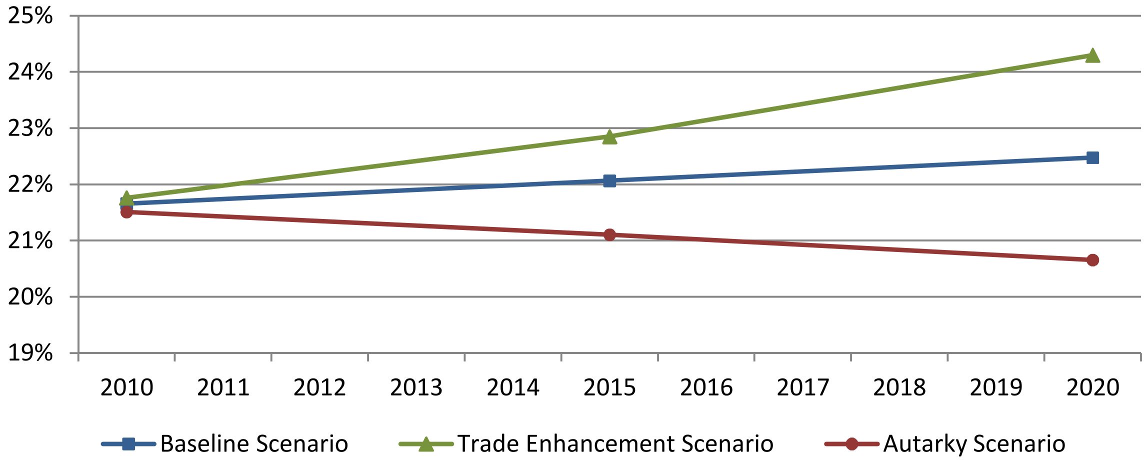


Figure 14. Share of Wind Power relative to Total Power Generated within the European Union

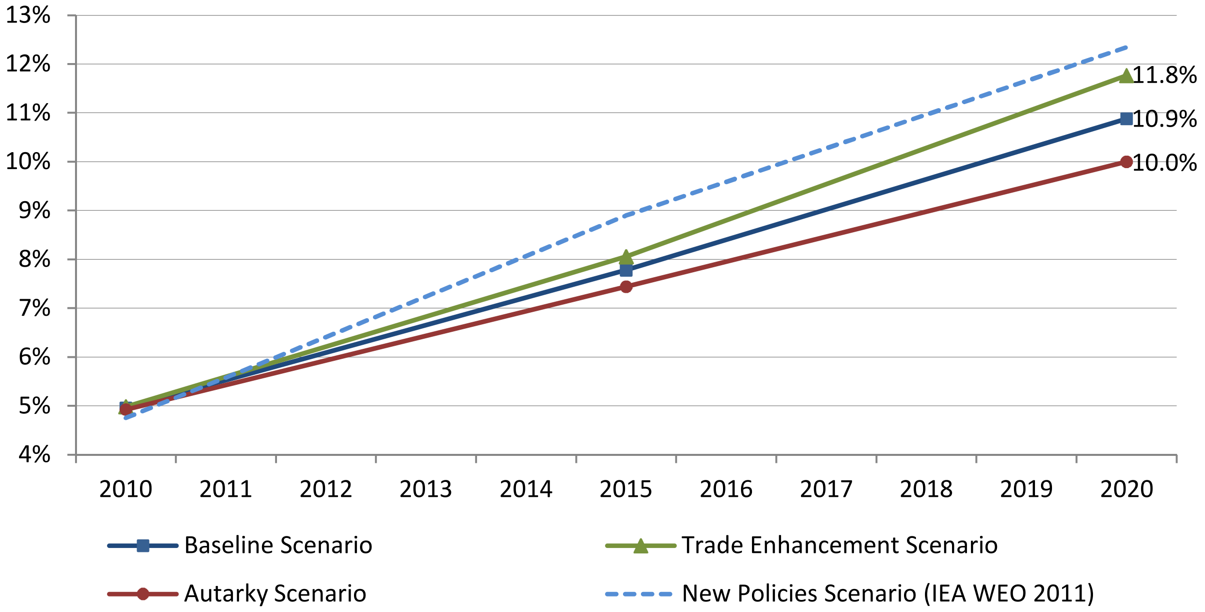
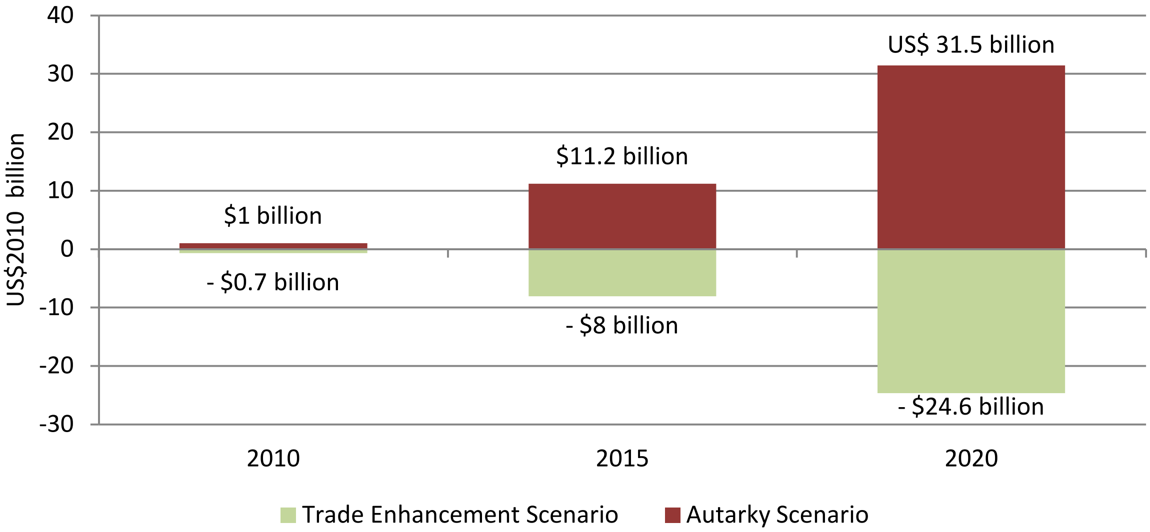


Figure 15. Relative additional cost of restrained cross-border electricity trade within the European Union



7. Conclusions & Policy Implications

Many OECD governments have established ambitious targets for the penetration of renewable energy. Wind and solar power are the renewable energy sources which are growing the fastest and which will have to become increasingly important elements in the electricity supply mix if ambitious targets are to be met. However, the generation of electricity from these sources is variable and unpredictable. This combination of variability and unpredictability, termed intermittency, poses significant challenges for grid operators since electricity supply and demand needs to be in balance on a continuous basis. While investment in a wide portfolio of renewable energy sources and the spatial dispersion of their location can reduce the risk of loss of load by reducing the correlation in their peaks and troughs, this is not likely to be sufficient as penetration rates rise. Investment in increased capacity of intermittent electricity power sources needs to be complemented with other measures in order to reduce the risk of loss of load and maximise the use of installed intermittent renewable power capacity.

In particular, measures that increase grid flexibility and transmission capacity are keys to ensuring an efficient use of the intermittent renewable capital stock. Grid flexibility can be achieved through the use of dispatchable power plants (principally gas and hydro), but also energy storage facilities (pumped hydro and advanced energy storage), and advanced grid management (including smart grid technologies). Increased transmission capacity through investment in high-voltage transmission lines allows for the more efficient exploitation of widely-dispersed generating sources within the grid. This can be complemented with high-capacity interconnectors which allow for the greater integration of grids (including cross-border trade).

In this study we have assessed the effect of different factors on the capacity utilisation of wind power plants. The model developed here focuses on wind energy since it is the most widely deployed, variable and unpredictable among intermittent renewables. However, the analysis is of broader relevance since it also applies to solar photovoltaic and marine energy sources. Two samples are estimated over the period 1990-2009, 21 European countries and a broader sample including 10 other OECD economies. A measure of available wind power was constructed based on monthly observations of average wind speed at wind power plants. In line with the theoretical model presented, a number of other explanatory variables which are subject to policy intervention are included, namely: i) dispatchable power; ii) storage capacity; iii) transmission capacity; and iv) electricity trade.

In all estimated models the different explanatory variables of interest are interacted with dummy variables reflecting the extent of capacity penetration of wind power. This elaboration is consistent with the conceptual discussion presented and the theoretical model developed. While grid capacity and dispatchable power have a constant impact over different capacity penetration rates, it is found that energy storage (pumped hydro) has an increasing impact on wind plant capacity utilisation with increasing capacity penetration. In the case of electricity trade the effect only becomes statistically significant once a penetration rate equal to the upper threshold is exceeded. However, this is equal to 3% penetration[47] (for the European sample), indicating that trade will have positive consequences for most countries as target objectives are approached.

The results of the model have important implications for the efficacy of different measures adopted to facilitate the integration of intermittent renewable energy plants in the grid. Further work will assess the costs and benefits of policy incentives which influence the different power balancing strategies. However, some general conclusions can be drawn from the results presented thus far. As the penetration of intermittent renewable increases it is necessary to:

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[47] This roughly corresponds to 1.5% in terms of wind power penetration (share of wind power relative to total power generated).

- Ensure investments in quality and capacity of the grid keeps pace with investment in intermittent renewable generating capacity;
- Provide incentives to allow the owners of dispatchable power plants to receive the option value associated with their availability as balancing power (and strategic reserves in the event of emergencies);
- Encourage energy systems integration (e.g. CHP) and demand management (i.e. smart meters) as a means to help balance supply and demand;
- Reduce existing constraints on trade in electricity (including those which arise out of renewable energy support policies); and,
- Encourage the continued innovation in advanced energy storage and grid management technologies.

The policy challenge is to ensure that incentives across these different strategies are aligned. The benefits in terms of IR capacity utilisation associated with each strategy will vary and this should be reflected in the different mechanisms at the policymakers' and regulators' disposal. This includes network user charges, financing of investments in interconnectors, capacity payments for balancing power and strategic reserves, public R&D support for advanced grid management and storage, programmes to encourage diffusion of smart meters, etc… Increased penetration of IR sources requires a rebalancing of policy efforts, with less of an exclusive focus on direct support measures for IR generation (i.e. feed-in tariffs and renewable portfolio standards).

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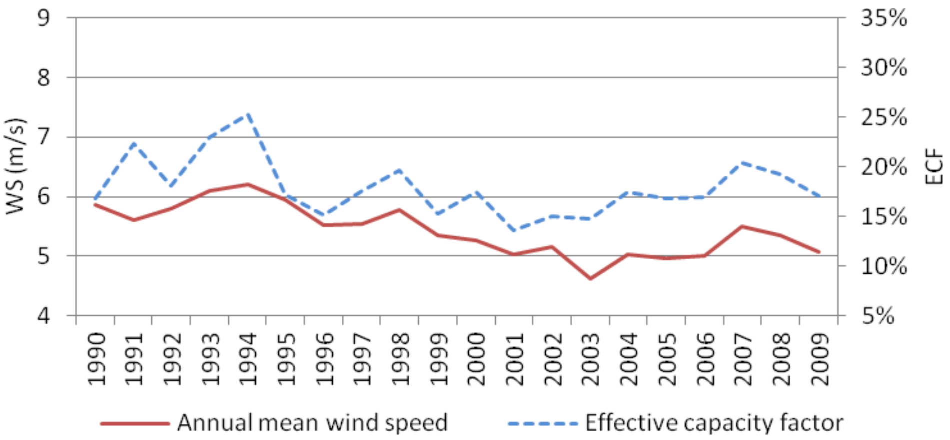
ANNEX 1. RELATIONSHIP BETWEEN WIND SPEED AND ECF

To gauge the accuracy of the calculated wind speed variable (*WS*), we examined its statistical relationship with *ECF.* In our sample, the Pearson correlation ranges between -.80 to .70 (see also Figures A1-A3). According to Ela (2009), the more often a wind generator is producing at less than potential, the more the correlation between wind speed and wind power is skewed. This result also applies to some extent at the country level, implying that wind power production will be less correlated with wind speed as wind farms are run below full potential.

Interestingly, in the case of Germany the two series have become almost perfectly correlated after 2003. Most likely, this can be explained by the Renewable Energy Sources Act[60] implemented in Germany in 2004. Under this policy, the four German transmission system operators are mandated to purchase and transmit all electricity produced from renewable sources[61], in priority. On the one hand short-run marginal costs tend to zero and production is subsidized by Feed-in Tariffs (FiT), while on the other hand all generated renewable power is guaranteed for priority purchase and transmission. In other terms, “mandated purchase” forces grid operators to use all available flexible resources in accordance with renewable power generation, so that production from renewable sources is maximized with respect to technological constraints. Therefore, we expect the implementation of priority dispatch in Germany to have increased the correlation between wind speed and wind plants capacity utilisation at the country scale. For the period 2003-2009, the correlation coefficient of 0.99 between *WS* and *ECF* is found for Germany, whereas it drops down to 0.65 when including pre-2003 observations.

Figure A1. Wind Speed and Effective Capacity Factor for Germany (1990-2009)



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[60] Erneuerbare-Energien-Gesetz (EEG).

[61] Such plants are granted priority access to the grid. There is obviously an upper limit to avoid amounts of wind power that might be harmful for the grid. See Eclareon (2011).

Figure A2. Wind Speed and Effective Capacity Factor for the United Kingdom (1990-2009)

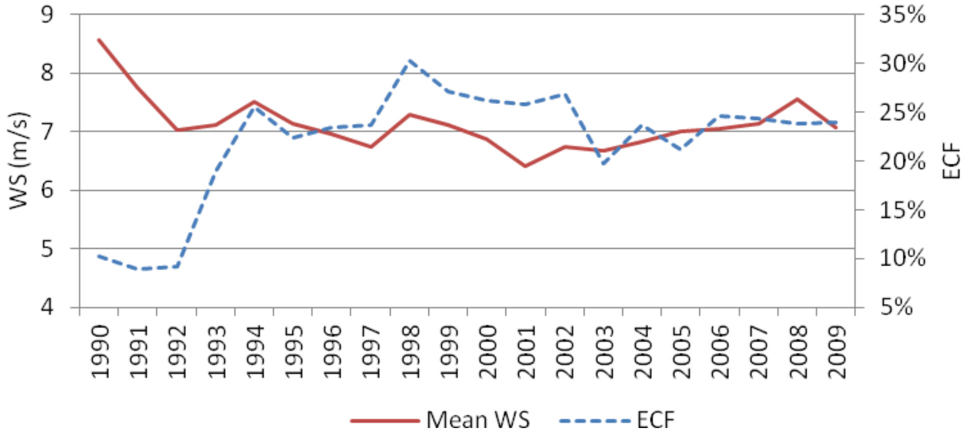
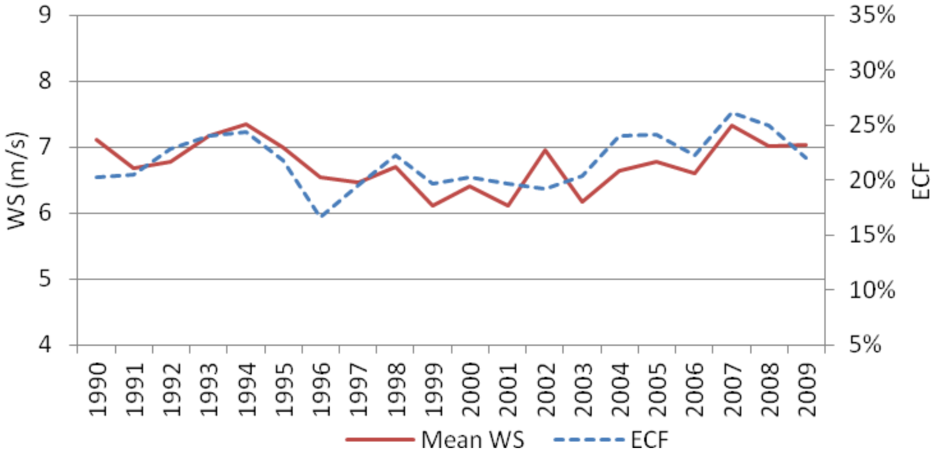


Figure A3. Wind Speed and Effective Capacity Factor for Denmark (1990-2009)



ANNEX 2. RELATIVE WIND RESOURCE OF NEW WIND GENERATION SITES

Many renewable energy technologies are site-specific in the sense that they must be installed where the renewable resource is adequate for production. As installed capacity of wind is growing in OECD countries, it is interesting to assess whether there has been some “learning” in selecting wind farms installation sites, or rather whether new turbines are being built on sites with lower wind resource due to a shortage of good sites.

Our wind speed and wind farms location data allow to assess the wind resource of one generation site relative to another. The following methodology is used for relative wind resource assessment. First, a countrywide long-term average wind speed over 20 years weighted by installed wind generation capacity is derived from monthly average wind speed data available in the NCEP/NCAR database. Similar long-term average wind speeds are computed for each of the wind farms sites in our data sample. Therefore, each site’s wind resource may be compared to the average wind resource on a country’s wind farms sites. This gives a measure of the relative wind resource of all wind farms sites in 31 OECD countries. Finally relative wind resource is averaged for all new wind farms sites for each year (where new sites are considered as those where no wind turbine were built ever before the year of interest). This relative average wind resource of new wind sites can be used to assess whether recent wind farms are constructed in regions with greater wind resource because of a learning effect, or with lower resource because best spots are already occupied.

Figure A4 to A6 plot the relative average wind resource of new wind generation sites for three OECD countries. It appears that best sites were primarily chosen in Australia although relative wind resource of new sites is more or less constant afterwards. On one hand, in Germany, relative wind resource of new generation sites exhibits a decreasing trend over time. This phenomenon is likely due to the limited availability of sites with great wind resource in the country, naturally leading to a shortage in good wind sites. On the contrary, the time trend for the United States is upward-sloping. One interpretation may be that there is some learning related to picking wind farms sites and better available technologies to effectively reach the best wind spots.

Figure A4. Relative average wind resource of new wind generation sites: Australia

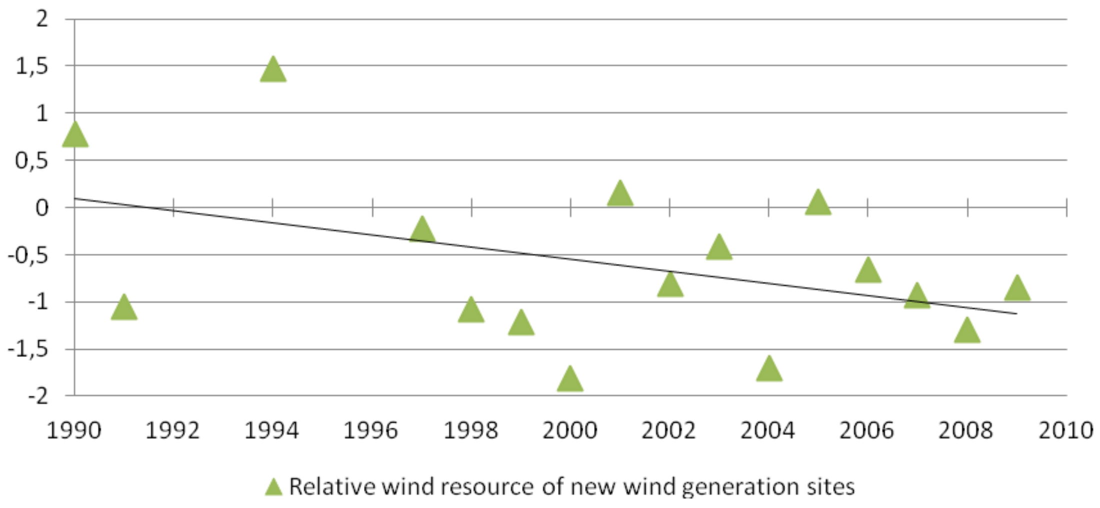


Figure A5. Relative average wind resource of new wind generation sites: Germany

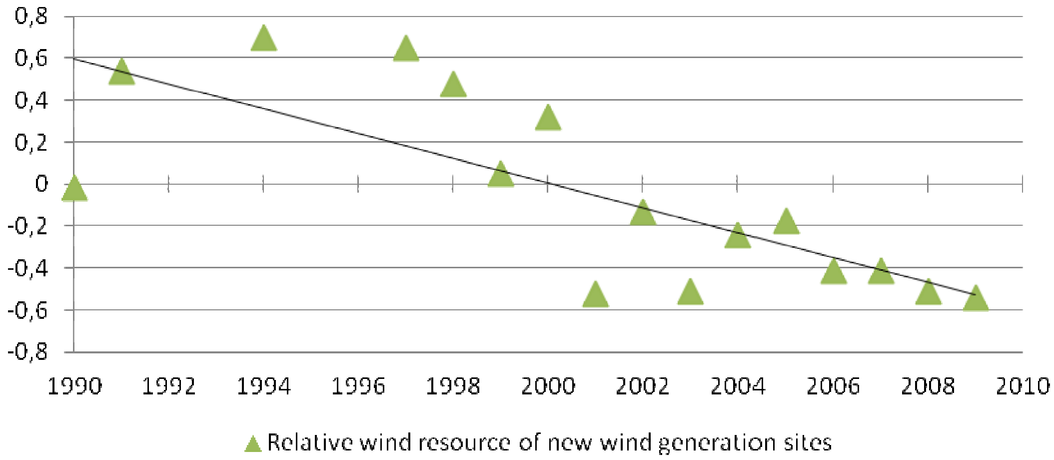


Figure A6. Relative average wind resource of new wind generation sites: United States