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Design and operation of power systems with large amounts of wind power

Final summary report, IEA WIND Task 25, Phase three 2012–2014

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Design and operation of power systems with large amounts of wind power

Final summary report, IEA WIND Task 25, Phase three 2012–2014

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Preface

A research and development (R&D) task on the Design and Operation of Power Systems with Large Amounts of Wind Power was formed in 2006 within the International Energy Agency (IEA) Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Turbine Systems (http://www.ieawind.org) as Wind Task 25. The aim of this R&D task is to collect and share information on the experiences gained and the studies made on power system impacts of wind power and to review methodologies, tools, and data used. The following countries and institutes have been involved in the collaboration:

- Canada: Hydro Québec's Research Institute (IREQ)
- China: State Grid Energy Research Institute (SGERI)
- Denmark: Technical University of Denmark (DTU); Energinet.dk
- European Wind Energy Association (EWEA), now WindEurope
- Finland (operating agent): Technical Research Centre of Finland (VTT)
- Germany: Fraunhofer Institute for Wind Energy and Energy System Technology (Fraunhofer-IWES); Research Centre for Energy Economics (FfE)
- Ireland: Sustainable Energy Authority of Ireland (SEIA); University College Dublin (UCD)
- Italy: Terna
- Japan: University of Kansai; Central Research Institute of Electric Power Industry (CRIEPI); University of Tokyo
- Norway: Foundation for Scientific and Industrial Research (SINTEF)
- Netherlands: Delft University of Technology (TUDelft); TenneT
- Portugal: National Laboratory on Energy and Geology (LNEG); Institute for Systems and Computer Engineering, Technology, and Science (INESC-TEC)
- Spain: University of Castilla La Mancha
- Sweden: Royal Institute of Technology (KTH)
- United Kingdom: Centre for Sustainable Electricity and Distributed Generation (Imperial College London and Strathclyde University)
- United States: National Renewable Energy Laboratory (NREL); Utility Variable-Generation Integration Group (UVIG); U.S. Department of Energy (DOE).

IEA Wind Task 25 produced a report in 2007 on the state-of-the-art knowledge and results that had been gathered so far that was published in the VTT Working Papers series. Summary reports of two subsequent phases have also been published by

VTT: 2009 (VTT Research Notes 2493) and 2013 (VTT Technology T75). These reports presented summaries of selected, recently finished studies. In addition, IEA Wind Task 25 developed guidelines on the recommended methodologies when estimating the system impacts and costs of wind power integration; this was published in 2013 as RP16 of IEA Wind. All of these reports are available on the IEA Wind Task 25 website: http://www.ieawind.org/task_25.html#.

This report summarises the results of the third three-year phase. The work continues with a fourth three-year period (2015–2017).

Sintef would like to acknowledge the NOWITECH research centre for financially supporting our participation in the IEA Task25 activities.

June 2016, Authors

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Abstract

List of acronyms

FACTS	Flexible AC Transmission Systems
FERC	Federal Energy Regulatory Commission
FRT	Fault-Ride-Through, capability of grid assets to stay connected to the grid during short-circuit faults of short duration
HVDC	High Voltage Direct Current
ISO	Independent System Operator
MAE	Mean Absolute Error
NWP	Numerical Weather Prediction
PSS	Power System Stabiliser
RMSE	Root-mean-square-error
TSO	Transmission system operator
TYNDP	Ten year network development plan
UCED	Unit Commitment and Economic Dispatch model
VSC	Voltage Source Converter

.

Executive summary

This report summarises recent findings on wind integration from the 15 countries participating in the International Energy Agency (IEA) Wind collaboration research Task 25 from 2012–2014. Both real experiences and studies are reported. Many wind integration studies incorporate solar energy, and most of the results discussed here are valid for other variable renewables in addition to wind.

The national case studies address several impacts of wind power on electric power systems. In this report, they are grouped under long-term planning issues and short-term operational impacts. Long-term planning issues include grid planning and capacity adequacy. Short-term operational impacts include reliability, stability, reserves, and maximising the value of wind in operational timescales (balancing related issues). The first section presents the variability and uncertainty of power system-wide wind power, and the last section presents recent wind integration studies for higher shares of wind power. Appendix provides a summary of ongoing research in the national projects contributing to Task 25 from 2015–2017.

Variability and uncertainty of wind power – an important input

The characteristics of variability and uncertainty in wind power are presented from experiences of measured data from large-scale wind power production and forecasting. There is a significant geographic smoothing effect in both variability and uncertainty of wind power when looking at power system-wide areas. Failure to capture this smoothing effect will affect the estimates for wind power impacts on power systems.

The smoothing effect is shown in the measured extreme variations and extreme forecast errors, which are relatively smaller for larger areas. Variability is also lower for shorter timescales. It has been found that there is a close to linear relationship between variability and predictability. A lower variability of wind generation also leads to reduced forecast errors. Regarding day-ahead and 1-hour shortest-term forecasts, improvements up to 50% and even 80% in terms of the mean absolute error (MAE) are expected by an aggregation of single wind power plants to a region such as Germany. Up until now, advanced forecast systems led to MAE values of approximately 1% of the installed capacity for 1-hour-ahead and 3% for day-ahead forecasts Germany's total wind power production.

Offshore wind power will present more variability and uncertainty if a large part of wind power generation is concentrated in a smaller area. Storm situations when extreme ramping occurs may be particularly challenging. Power ramping in extreme wind events can be reduced by modifying the control of the individual wind turbines such that they continue producing at higher wind speeds, albeit at a reduced level. This will also improve the short-term forecasts of offshore wind; these forecasts are critical when managing extreme storm situations.

Wind power in long term planning for grid and generation adequacy

The grid reinforcement needed for wind power is very dependent on where the wind power plants are located relative to load and existing grid infrastructure, and it is expected that results vary from one country to another. Not many studies report the costs of grid reinforcements caused by wind power because transmission lines in most cases are used for multiple purposes. In previous studies, only Portugal made the effort to allocate costs among different needs. In the combined efforts for ten-year network development plans (TYNDP) from the European transmission system operators (TSOs), estimates on allocation are depicted on a general level as the share of new grid that will be needed for renewables, markets, and security. The national results reported in recent studies also address flexibility needs mitigated through transmission to reduce curtailments of wind power and to access flexibility from hydropower. The large offshore wind power plants in Europe have launched research on offshore grids. It is evident from several studies that long-term strategies for offshore grids among several countries should be done in a coordinated way to ensure optimal developments.

Wind power's contribution to a system's generation capacity adequacy is its capacity value. In most countries, this is not a critical question in the starting phase of wind power deployment; however, there is already experience from conventional power plants withdrawing from the market due to reduced operating times and full load hours, leading to low income. This will raise the question of resource (or generation) adequacy in a power system. Wind power will provide more capacity and thus add to the reliability of the power system; however, the benefits of added capacity vary depending on how much wind resource is available during times of peak loads. The capacity value of wind power decreases with an increasing share or wind power in the system. The results summarised in this report show that most countries have a capacity value of 20–35% of installed capacity for the first 5–10% share of wind; however, for a 20% share of wind in a system, the capacity value is above 20% of the installed capacity for only one study assuming a very large interconnected system. Aggregation benefits apply to capacity value calculations—for larger geographical areas, the capacity value will be higher. Also, a large range is shown for a same share of wind: from 40% in situations where high wind power generation at times of peak load prevail to 5% if regional wind power output profiles correlate negatively with the system load profile (often low wind power generation at times of peak load).

Impacts of wind power on short-term reliability

The impact of wind power on power system dynamics is becoming increasingly apparent with larger shares of wind power, and it will become more important to study this aspect in wind integration studies. Wind generation, by its mere presence, does not necessarily worsen the stability of a system, but it does change its characteristics because it is increasingly connected via power electronic interfaces. Wind power plants can offer a promising option for defence against short-term voltage and frequency instability, and system capabilities can be enhanced through intelligent coordination of the controllers of the power electronic converters. Recent work has also taken into account possibilities for wind power plants to support the grid.

Results of transient stability simulations for after-fault situations for up to a 40% share of wind energy in the system show that this is not a challenging issue. Regarding voltage stability, it will be crucial to use wind power plant capabilities. Frequency stability challenges depend on the system size, share of wind power, and applied control strategies. With lower levels of directly connected, synchronous, large rotating machines, the inertia in the system will decrease, and there is a risk that after a failure at a large power plant the frequency will drop to a level that is too low before the automatic frequency control has stabilised the system. This was first studied in smaller systems such as Ireland, but it is increasingly being studied for larger areas that have higher shares of wind power. Frequency drops can be significant in cases of high levels of wind and solar energy, and studies of wind power providing very fast response to support the system are ongoing.

The impact of wind power on short-term balancing and frequency control has been the focus of many integration studies for decades. The reserves are operated according to total system net imbalances for generation and demand, not for each individual source of imbalance. A large range of results show estimates of increases in reserve requirements. The forecast horizon timescale is a crucial assumption when determining how much reserve needs to be allocated because the uncertainty of wind power will reduce more significantly than the uncertainty of demand at shorter timescales:

- If only hourly variability of wind and load is taken into account when estimating the increase in the short-term reserve requirement, the results for most studies are 3% of installed wind capacity or less, with wind shares of up to 20% of gross demand.
- When 4-hour forecast errors of wind power and load are taken into account, an increase in the short-term reserve requirement of up to 10% of installed wind capacity has been reported for wind shares of 7–20% of gross demand.
- When day-ahead uncertainties are taken as the basis of reserve allocation, wind power will cause increases of up to 18% of installed wind power capacity.

These increases in reserve requirement are calculated for the worst case; however, this does not necessarily mean that new investments are required for reserve capacity. The experience so far is that wind power has not caused investments for new reserve capacity; however, some new pumped hydro schemes are planned in the Iberian Peninsula to manage wind shares of more than 20% in the future. New studies for higher shares of wind energy are increasingly looking at the dynamic allocation of reserves: if allocation is estimated once per day for the next day instead of using the same reserve requirement for all days, the low-wind days will make less requirements on the system. The time steps chosen for dispatch and market operation can also influence the quantity and type of reserve required for balancing. For example, markets that operate at 5 minute time steps can automatically extract balancing capability from the generators that will ramp to fulfil their schedule for the next 5-minute period.

Maximising the value of wind power in operation

The value of wind power is maximised when there is no need to curtail any available wind power and when the impact on other power plants in the operational timescale is minimised.

Experiences in wind power curtailment show that curtailments do not occur in smaller shares of 5–10% of yearly electricity consumption if there are no severe transmission bottlenecks and wind power is dispatched first among the low marginal cost generation. However, in some countries substantial curtailments (10–20% of wind generation) started occurring at lower shares of wind. The mitigation efforts regarding transmission expansion in these countries have resulted in a reduction in curtailment rates with increasing wind power. Estimating future curtailments of wind energy as well as mitigation options to reduce them is emerging as one key result in integration studies. The participation of wind power generators in frequency control (ancillary services market) will decrease the overall curtailed renewable generation with large shares of wind power in the system because this will allow other generation to shut down and make room for more wind.

Balancing cost has traditionally been the main issue that many integration studies try to estimate. It is becoming less of an issue in countries where experi-ences in wind integration are accumulating. Analyses regarding integration costs evolve towards comparing total system costs for different future scenarios showing both operational and investment costs. In countries where wind power is out in the markets, balancing is paid by the operators in imbalance costs. There is some recorded experience in the actual balancing of costs for power systems that have growing shares of wind power. In Italy, costs have almost doubled; whereas in Germany, balancing costs have actually been reduced by 50% despite a growing share of wind and solar power because of the more profound impact of sharing balancing resources with the balancing areas.

Increased balancing due to thermal power plant cycling has been studied in detail to confirm that cycling costs are relatively small compared to the reduction in operating costs that can be achieved with wind and solar energy. The impact on emissions is also very small. Wind power reduces CO_2 emissions for approximate-ly 0.3–0.4 Mt/MWh when replacing mainly gas and up to 0.7 Mt/MWh when replac-ing mainly coal-powered generation.

Measures to enhance the balancing task with high shares of wind power include operational practices and markets, demand-side flexibility, and storage. Electricity markets that have cross-border trades of intraday and balancing resources and emerging ancillary services markets are considered positive developments for future large shares of wind power. Energy systems integration among the electricity, gas, and heat sectors is studied for future power systems that have high shares of renewables. Enhancing the use of hydropower storage to balance larger systems is another promising option. Electricity storage is seeing initial applications by system operators in places that have limited transmission capacity. Electricity storage is still not as cost-effective in larger power systems as other means of flexibility, but different forms of storage have a large role in the emerging studies for systems that have 100% renewables.

Integration studies for power systems that have >40% shares of wind and solar are pushing the limits of how much variable generation can be integrated. The results so far are promising, and the work is ongoing, with more detailed modelling possibilities in the futuretime-scale.

1. Introduction

The existing targets for wind power anticipate a high penetration of wind power in many countries. It is technically possible to integrate very large amounts of wind capacity in power systems, with the limits arising from how much can be integrated at socially and economically acceptable costs. There is already practical experience from wind integration (Figure 1) from Denmark, Portugal, Spain, and Ireland with more than 15% penetration levels on an annual basis (in electrical energy). Also, in several regions – including Northern Germany, the Midwest United States, Central-Southern Italy, Sicily, and Sardinia – penetration levels of more than 20% give insights of how to cope with higher shares of wind power. In several countries, mainly Germany, Italy and Greece, there is considerable share of solar energy on top of wind energy to make the variable generation challenge higher than depicted in Figure 1.

Wind power production introduces additional variability and uncertainty into the operation of the power system, over and above that which is contributed by load and other generation technologies. To meet this challenge, there is a need for more flexibility in the power system. The increased need for flexibility required depends on how much wind power is embedded in the system as well as how much flexibility already exists in the power system.

Because system impact studies are often the first steps taken towards defining feasible wind penetration targets within each country or power system control area, it is important that commonly accepted standard methodologies related to these issues are applied. The circumstances in each country, state, or power system are unique with regard to wind integration. Numerous reports have been published in many countries investigating the power system impacts of wind generation. The results on the technical constraints and costs of wind integration differ, and comparisons are difficult to make due to different methodologies, data and tools used, as well as terminology and metrics in representing the results. Estimating the cost of impacts has proved to be a challenging task as the comparison to a base case will impact the results and is not straightforward to make in a fair and transparent way. Some efforts on compiling results have been made by DeMeo et al. (2005), Smith et al. (2007), UKERC (2006), Ackermann & Kuwahata (2011) and O'Malley et al. in IPCC (2011). Due to a lack of detailed information on the methodologies used, a direct comparison can only be made with few results.

An effort for more in-depth review of the studies was made under this international collaboration in the state-of-the-art report (Holttinen et al., 2007) and summary reports (Holttinen et al., 2009; Holttinen et al., 2013), of which this report is an update with more recent results.

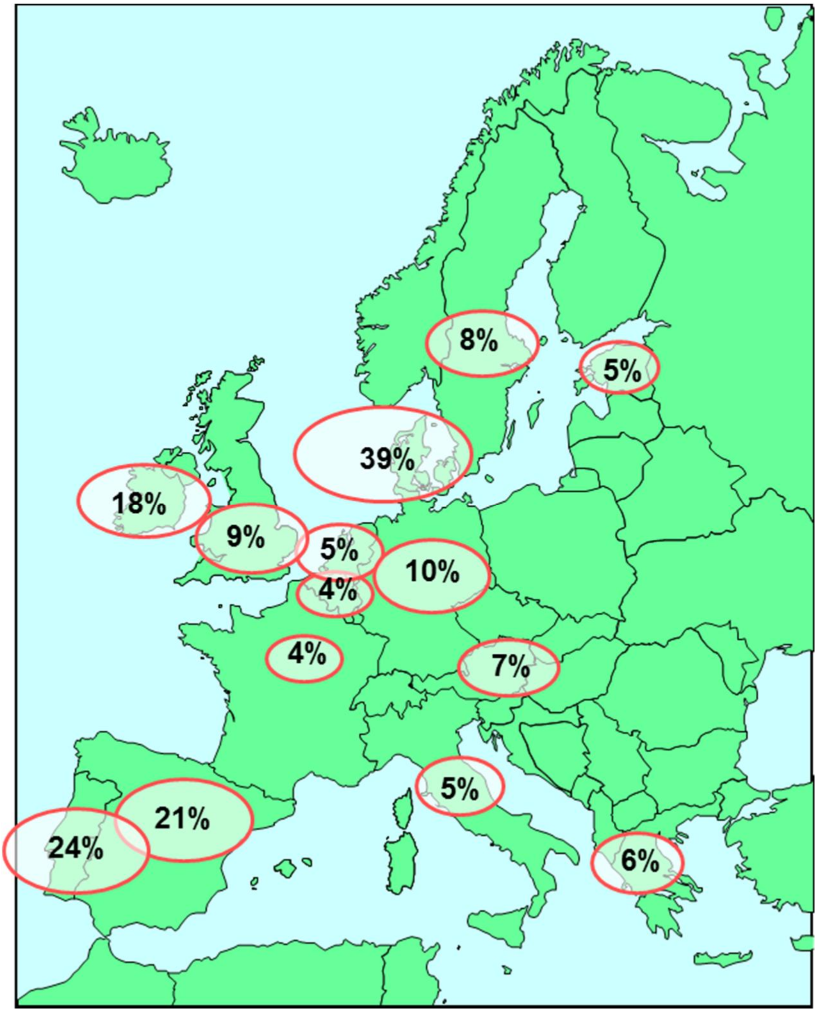


Figure 1. This map highlights wind generation share of total electricity consumption in 2014 in European countries that have reached a 4% share. In the European Union (EU), wind share exceeded 9% in 2014; in the United States and Australia, wind share is 4%; and in China, it is 2% (source for wind shares: IEA WIND, 2015).

Table 1. Wind and power system statistics, year 2014. Source: IEA WIND, 2015; IEEE P&E magazine in Nov/Dec Issue with data from Energinet.dk, BNetzA, German TSOs, REE, EirGrid, EdF, Terna. Hydro-Quebec Annual Report 2015, web site and Energy Supply Plan. European countries Export capacity as maximum hourly day-ahead NTC value available for all interconnections, hourly data available from https://transparency.entsoe.eu/content/static_content/Static%20content/legacy%20data/legacy%20data2014.html

	Load			Export capacity	Wind power end 2014		Wind share		
	Peak (MW)	**Min (MW)**	**TWh/a**	**MW**	**MW**	**TWh/a**	**% of gross demand**	**% of peak load**	**% of min load + export capacity**
Québec	38743	14500	184	7974	2857	6.8	3.7%	7.4%	12.7%
Denmark	6 400	3000	33.5	6790	4 855	13.1	39.1%	75.9%	52.1%
Finland	14 000	6000	83	5000	627	1.1	1.3%	4.5%	6.7%
Germany	82 500	41 000	539.3	33 800	40 456	56	10.4%	49.0%	78.2%
Ireland	6500	2500	26.6	1000	2 230	5.1	19.2%	34.3%	68.6%
Italy	51 550	18740	310.5	2715	8 700	15.2	4.9%	16.9%	40.5%
Japan	191000	90000	965.2	0	2 788	5.1	0.5%	1.5%	3.1%
NL	25200	9000	120.9	7350	2 753	5.8	4.8%	10.9%	18.8%
Norway	24000	8000	127	6083	856	2.2	1.7%	3.6%	6.5%
Portugal	8800	4560	50.3	3000	4953	12.1	24.1%	56.3%	65.5%
Spain	43 450	15300	243.5	4100	22 845	50.7	20.8%	52.6%	118.4%
Sweden	26000	13000	145	9165	5425	11.6	8.0%	20.9%	23.9%
GB	50930	18060	290.1	4000	12 808	31.6	10.9%	25.1%	58.6%
ERCOT/US	66464	24083	340	856	11 601	36.1	10.6%	17.5	46.5%

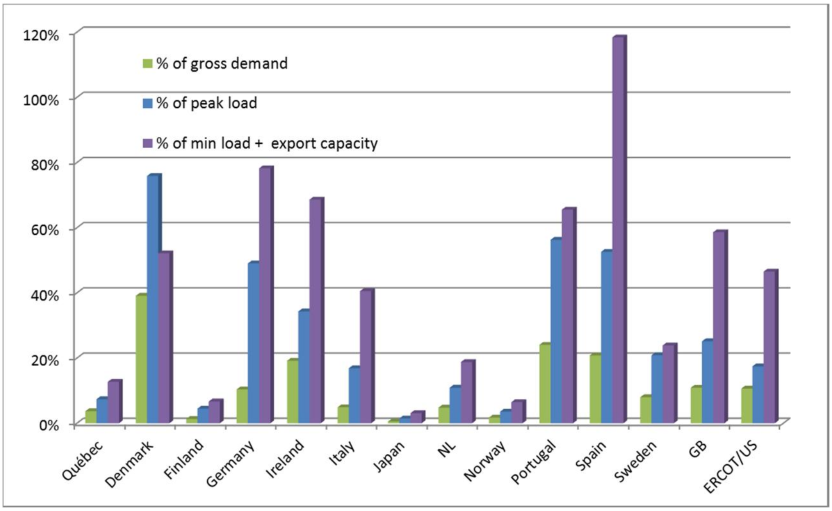


Figure 2. Wind share in the studied countries and areas, measured in three ways: wind generation as share of electricity consumed (% of gross demand), wind capacity as share of peak load capacity and wind capacity as share of minimum load plus export capacity (European countries as maximum hourly day-ahead NTC value available for all interconnections).

The national case studies address different impacts: balancing the power system on different operational time scales; grid congestion, reinforcement, and stability; and power adequacy. Reasons underlying the wide range for wind integration impacts include definitions for wind share in the system, operational reserve types, and costs; different power system and load characteristics and operational rules; assumptions on the variability of wind, generation mix, fuel costs, and the size of balancing area; and assumptions on the available interconnection capacity.

In many studies, estimates for integration costs are presented. Integration cost can be divided into different components arising from the increase in the operational balancing cost and grid expansion cost. The value of the capacity value of wind power can also be stated. In most case studies, a comparison with other alternatives to wind has not been studied. When estimating the costs, allocation of system costs like new grid or reserve capacity to wind power can differ. It is challenging to allocate system costs for a single technology because the system services are there for all grid users, and integration cost is not observable. This inability to observe integration cost has resulted in multiple indirect methods for estimating it. In the case of an increased balancing requirement, it is important to note whether a market cost has been estimated or whether the results refer to technical cost for the power system. There is also benefit to adding wind power to power systems: it reduces the total operating costs and emissions as wind displaces fossil fuel use. When considering the question of integration costs, it is also important to keep in mind that all generation sources, including nuclear and fossil plants, have costs associated with managing them on the grid.

The case study results are summarised in four sections: first, Section 2 provides updated information on the variability and uncertainty of large-scale wind power, from reported experience. Sections 3 and 4 address the long term planning issues with wind power: grid planning and capacity adequacy. Sections 5 and 6 address the operational impacts: short term reliability (stability and reserves) and maximising the value in operational time-scales (balancing related issues). Section 7 summarises recent wind integration studies for higher shares of wind power and Section 8 concludes. Appendix provides a summary of on-going research in the national projects contributing to Task 25.

2. The inputs: variability and uncertainty of power system wide wind power

This chapter covers variability and predictability of wind power, from wind power generation and forecast data. Data for aggregated wind power covering larger, system and balancing area wide regions is important as an input to integration studies. Variability in wind power generation causes changes to the operation of conventional generation fleet, increasing ramping and starts/stops. Uncertainty leads to changes in shorter time scales (i.e., ramping) and can necessitate changes in operational conventions, such as reserve and market structures to enable shorter response time from the conventional generation fleet.

As will be more elaborated in following sections, wind is only one source of variability and uncertainty in the electric system. Electric demand, unscheduled equipment unavailability, run-of-river hydro or PV generation will add their share to the total aggregated variability in the power system. An operator must react to the net system variability and uncertainty and simply adding individually established impacts lends unneeded levels of reserves and overall inefficient management of the electric system. This is even more important to address when these sources are correlated, such as, for example, weather and environment dependant electric load and wind power.

There is a significant smoothing effect in both variability and uncertainty of wind power when looking at power system wide areas. Inability to capture this smoothing effect will impact the estimates for wind impacts on power systems. The uncertainty of future wind power production will further be reduced as more accurate forecasting methods are developed and operational practices evolve towards faster decisions with better forecast accuracy.

2.1 Variability

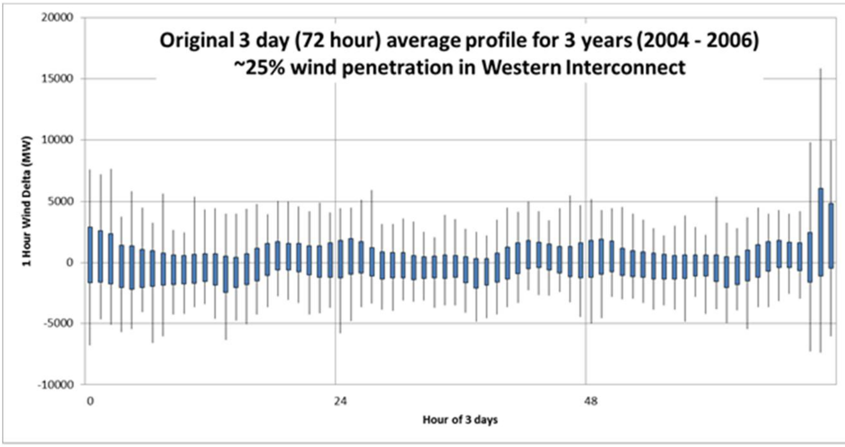
Variability of wind power decreases as the geographical dispersion of wind power capacity increases. Less variable wind power is easier to integrate. It is therefore important to capture the variability correctly in wind power integration studies. This section summarises recent findings on the variability and extreme ramps that large scale wind power may experience.

2.1.1 Caveats in measured and modelled data

In wind integration studies variability for a future wind power plant aggregation needs to be estimated. In many places realised wind power generation time series already exist that can be used as basis of the future estimated wind power production time series. Realised wind power data can be biased, since in future hub heights and the ratio between energy harvesting area and nameplate capacity can change affecting also variability. Also the dispersion can change considerably with new turbines. Often one example year is used, but individual years may not cover all critical weather situations.

If measured data is not available or is of limited quality, weather model generated data can also be used. This data may have biases due to model errors and due to assumptions needed for the conversion from wind speed to wind power. In general there is a much higher correlation between single sites based on the same weather analysis data as observed by real wind power plant measurements. Overestimating the correlation means underestimating the smoothing impact.

Numerical weather prediction modelling tools recreate the weather for any time and space, allowing a physically-consistent data set to accurately represent the smoothing that results from geographic dispersion (EWITS, 2010; NREL 2010). There can be anomalies discovered in that data set and analysis should be done to check the quality of the data and correct if necessary. For example, in WWSIS Phase 1 in the US, every 3 days there was a temporal seam in the simulated wind power data set that was created when the model was re-initialized with actual observational data. This created spikes in variability that are not representative of reality (EWITS, 2010). In Phase 2 of this study (Lew et al., 2013a), statistical methods were applied to bring the variability at these seams in line with what is expected. Figure 3 shows the average profile of the uncorrected data with the spike that occurs at the end of the 3-day period, and corrected data set that does not show the effect of the temporal seam at the end of 3 days (Lew et al., 2013a). These anomalies were not found in the US EWITS study (EWITS, 2010), and all subsequent work on this type of data sets at NREL have corrected this issue.



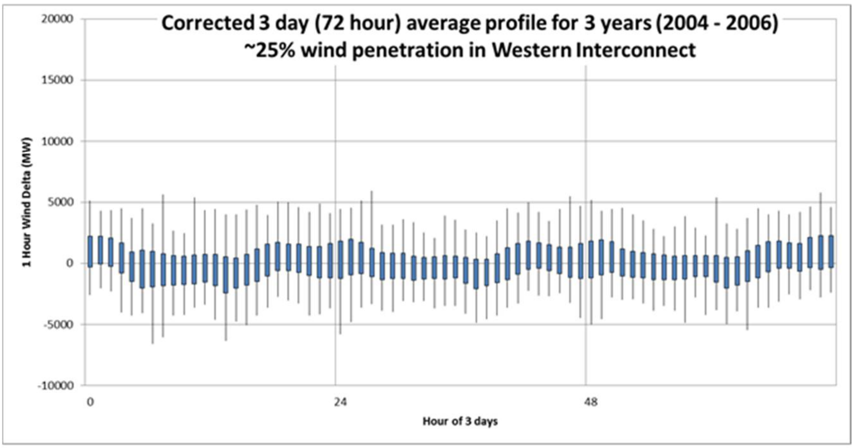
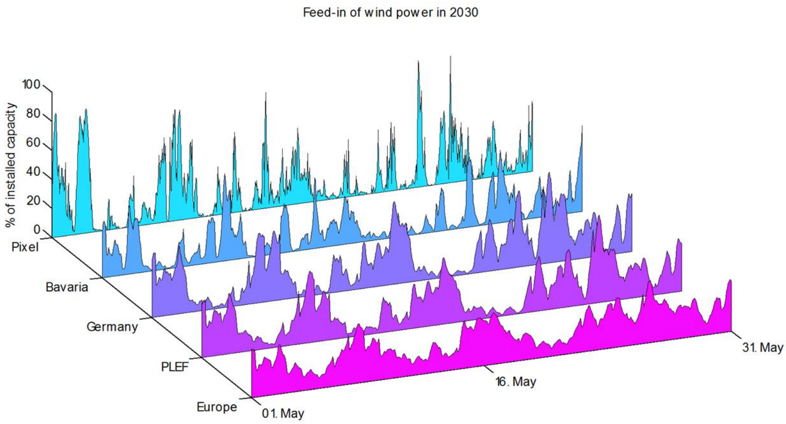


Figure 3. Example of potential errors in model data for wind power variability from West US. Original data with variability spike every 3 days (above) and corrected data without the artificially high variability (below). (Source: WWSIS Phase 2; see Lew et al., 2013a.)

2.1.2 Variability and smoothing impact of wind power covering large areas

An overview about the smoothing effect by comparing the measured time series of a single wind power plant, of a group of wind power plants and of the wind power production of complete Germany is shown in Figure 4.



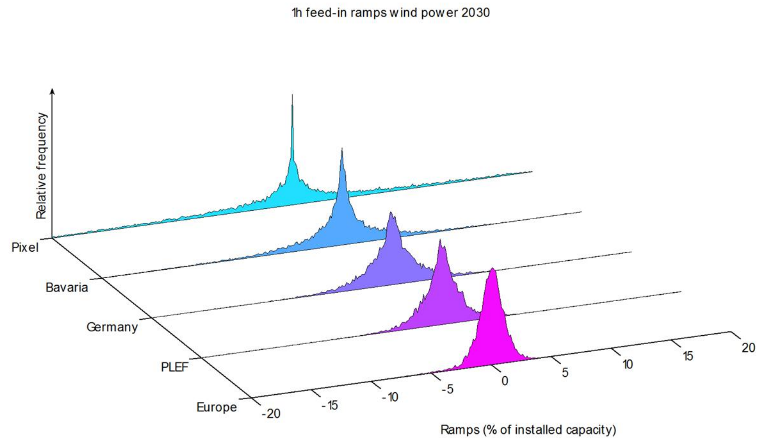


Figure 4. Illustration of the smoothing effect – large scale wind power production from a country, group of countries and Europe wide (upper graph), will see much less short term variability (hourly ramps, graph below). (Source: Fraunhofer IWES, 2015.) One pixel is equivalent to an area of 2.8 x 2.8 km. PLEF = Pentalateral Energy Forum (Benelux, Germany and France).

In Task 25 collaboration, real measured wind power production data was collected from countries that already had tens of separate wind power generation sites (Kiviluoma et al., 2015). There was a clear trend in decreasing variability when looking at larger areas (as function of mean distance between installed wind power megawatts, Figure 5). The variability did not markedly decrease with increasing number of sites. There was also a correlation of more variability from higher wind resource sites and years (with variability and capacity factor, Figure 6). Figure 7 displays hourly wind power ramp distributions as function of the level of output. The size of area correlates to larger variability.

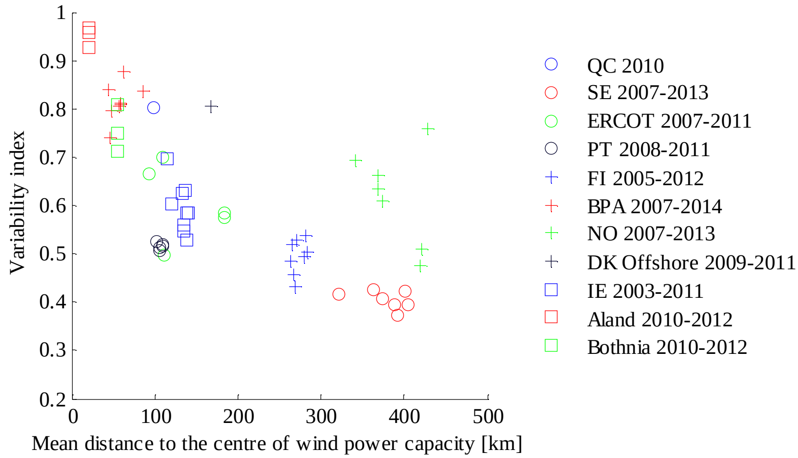


Figure 5. Variability index versus the mean distance to the capacity weighted geographical centre of wind the analysed wind power fleet. As dispersion grows, variability decreases. (Source: Kiviluoma et al., 2015.)

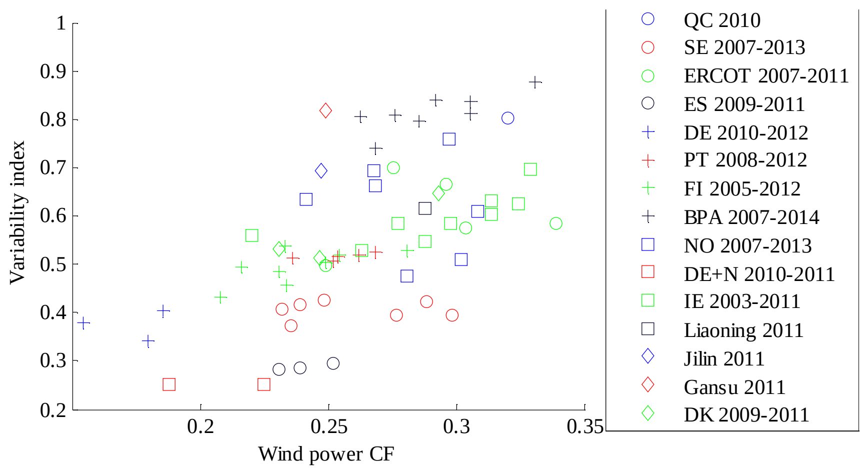


Figure 6. Variability index versus the capacity factor of wind power. (Source: Kiviluoma et al., 2015.)

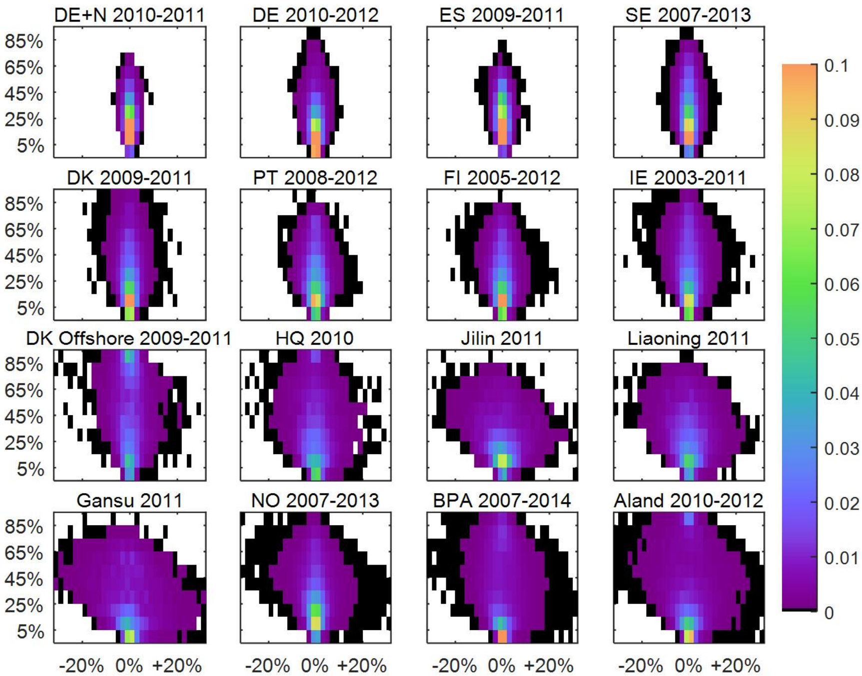


Figure 7. High ramps occur at the middle range of output level turbines, frequency of 60-minute wind ramps as a function of the output level at the start of the ramp. The data is binned according to the wind power output level (y-axis) and the wind power ramp (x-axis). (Source: Kiviluoma et al., 2015.)

2.1.3 Wind and solar variability

Wind variability is often considered in the context of other sources of variability that can be found on the power system. The Western Wind and Solar Integration study Phase 2 in US found that variability was dominated by solar energy, whereas uncertainty was dominated by wind power (Lew et al., 2013a).

In Portugal dynamic modelling of a hybrid wind-PV power plant assessed potential to smooth out power fluctuations. For this specific plant, installing PV overcapacity instead of more wind, does not significantly increase the maximum power fluctuations in any of the time-scales studied (30 minutes, 1 and 4 hours) (Rodrigues & Estanqueiro, 2011).

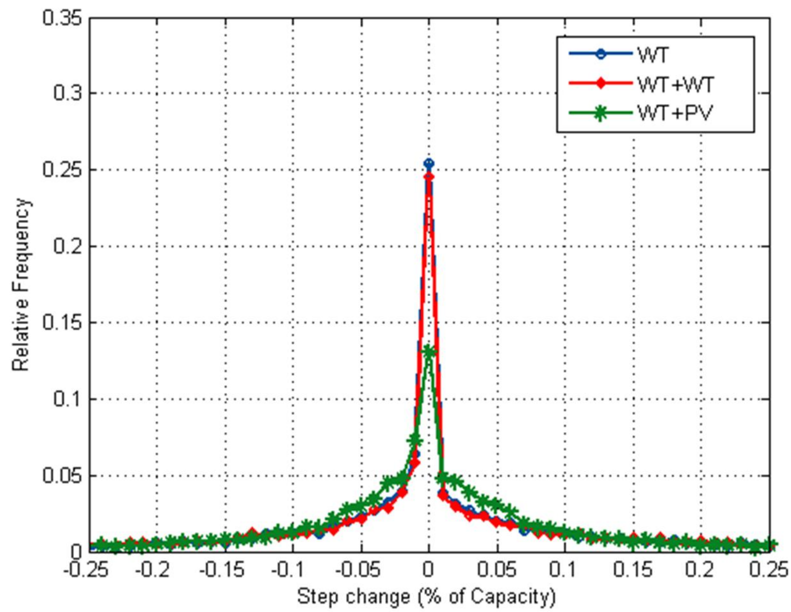


Figure 8. One hour step changes for: a wind power plant (blue) and for the same wind power plant with added wind (red) and PV (green) overcapacity. The additional installation of PV impact mainly fluctuations smaller than 10% of the installed capacity. (Rodrigues, 2012.)

2.1.4 Extreme ramps from wind power production

The maximum variations recorded from measured wind power production data from countries in different time-scales are presented in Table 2.

Table 2. Extreme variations of large-scale regional wind power, as a percent of installed capacity. Denmark, Portugal, Germany and Sweden data 2010–2011 from TSOs web pages (http://www.energinet.dk). Ireland 2011 data from EirGrid. Italy (Sicily island) data 2010–2011 from Terna, Finland data 2005–2011 from VTT. USA data 2007–2011 from NREL. The BPA data are mostly from sites inside an area of 60 x 60 km^2. China data from State Grid Corporation of China. Quebec data from Hydro Quebec. Spanish data from the Universidad de Castilla-La Mancha.

			10–15 minutes		**1 hour**		**4 hours**		**12 hours**	
Region	Region size	Number of sites	max decrease	max increase	max decrease	max increase	max decrease	max increase	max decrease	max increase
Italy (Sicily island)	25.711 km^2	>48	-49%	+46%	-50%	+49%	-58%	+47%	-67%	+68%
ES_2009_2011_10	800x900 km2	14-16	-7%	10%	-10%	10%	-26%	29%	-39%	39%
DE_2010_2012_15	400x400 km2	>100	-11%	12%	-10%	11%	-33%	34%	-53%	64%
PT_2008_2012_15	300x800 km2	>100	-16%	11%	-15%	19%	-47%	57%	-72%	70%
ERCOT_2008_2011_5	490x490 km2	25–55	-25%	25%	-41%	39%	-54%	61%	-77%	70%
BPA_2007_2014_5	300x200 km2	8–37	-32%	31%	-38%	50%	-71%	86%	-89%	93%
HQ_2012_60	300x500 km2				-20%	29%	-40%	68%	-78%	80%
IE_2003_2011	280x480 km2	>50			-27%	28%	-67%	69%	-86%	84%
FI_2005_2012_60	400x900 km2	30			-22%	24%	-52%	44%	-70%	78%
DK_2009_2011_60	300x300 km2	>100			-20%	21%	-47%	56%	-88%	96%
SE_2007_2013_60	400x900 km2	>100			-13%	13%	-35%	41%	-60%	64%
NO_2007_2013_60	1200x300 km2	9-20			-42%	64%	-61%	63%	-81%	80%
DE+Nordic_2010_2011_60	2300x1100 km2	>100			-6%	8%	-19%	23%	-30%	47%
Liaoning_2011_60	530x370 km2				-31%	29%	-46%	50%	-65%	72%
Jilin_2011_60	650x300 km2				-34%	34%	-66%	56%	-69%	73%
Gansu_2011_60	1655x530 km2				-43%	51%	-65%	72%	-72%	74%

Storm events can result in extreme variation from wind power when wind speeds are high enough to require wind turbines to shut down from full power (to protect the wind turbine). These events are quite rare and usually occur once in 1–3 years, depending on location. Extreme ramp rates recorded during storms are as follows:

- Denmark: The storm with the largest impact on the power system occurred on 28 October 2013. In the afternoon the wind speed exceeded by far the cut out wind speeds and the wind generation dropped from 3500 MW (installed wind capacity 3900 MW on land and 870 MW offshore) to about 1300 MW during 1 hour in the afternoon (2200 MW/h, 46% of capacity). For land based capacity the maximum ramp was 1380 MW/hour (35% of capacity). The largest observed downward ramp of wind was observed to about 200 MW (4%) in 5 minutes (for land based wind power -140 MW, 4%). When the storm had passed the wind turbines came back in operation later in the afternoon, where largest ramp for one hour was an increase with 1000 MW (21%) from 1100 MW to 2100 MW (for land-based 860 MW/hour, 22% of capacity, from 1350 MW to 2210 MW). The largest observed 5 min ramp was about 170 MW (4%) in 5 minutes (for land based 100 MW, 3% of capacity) (Energinet.dk, 2015).
- Germany: The time series of the German wide wind power production from 01/2012 to 04/2015 has been analyzed with respect to ramps and forecast errors. The installed capacity increased from 28575 MW in 01/2012 to 38104 MW in 04/2015. Storm events caused 60% of the 50 highest positive and negative ramps and forecast errors. The largest ramps were 5% of capacity downwards and 6% upwards in15 minutes, ±12% of capacity in an hour, and 45% downwards and 38% upwards in 5 hours.
- Portugal: There were several storm cases in winter 2009/10 when high ramps occurred: Nov 15th 2009 saw first 2.42 GW up ramp during 5.5 hours (72% of installed wind capacity) and then, two grid faults due to the storm in which more than 1.3 GW was lost and recovered in less than 15 minutes (about 52% of the wind generation). Jan 12th 2010 a ramp about 1 GW with one hour down 1.5 hours up (max ramp rate of 374 MW/15 min). Feb 23rd 2010 a ramp-down rate of 442 MW/15 min, after which the initial wind production level was recovered in one hour. In the recent years, the storm with the largest influence on the power system occurred on 18/19 January 2014 with an increase of 2.1 GW in 4 hours (45% of installed wind capacity) of the wind power production. March 28th 2013 had two highest ramp-up events observed during 15 min since 2012: 344 MW and 316 MW, respectively. The highest ramp-down event during 15 min occurred on Jan 9th 2013: 286 MW. No technical problems were reported by the Portuguese TSO during these wind power ramp events.
- Spain: examples of large ramp rates recorded during last years include a 3160 MW (14%) increase in 50 minutes (with a ramp rate of 3792 MW/h), and a 2874 MW (13%) decrease in 50 minutes (with a ramp rate of -3448 MW/h). In 2014 the minimum production was 139 MW and the maximum production reached 16729 MW (7–75% of installed). The most severe storm incident has been the extra-tropical, mid-

latitude cyclone Klaus on January 23–25, 2009, resulting in the disconnection of many wind power plants in northern areas of Spain, leading to a reduction of approximately 7000 MW of wind power in approximately 7 hours (less than 50% of installed capacity). (Source: REE[1]).

- Quebec: A large ramp rate was recorded in December 2011 with 600 MW in 5 hours (65% of capacity) or 14% per hour.
- Italy: In Sicily island (1391 MW wind in 2010 and 1750 MW in 2013) a maximum decrease of 1168 MW (approximately 67% of installed wind capacity) in 12 hours on March 1st 2013, and a maximum increase of 1189 MW (approximately 68% of installed wind capacity) in 12 hours on February 10, 2012 (Source: Terna[2]).

Because large storm fronts take 4–6 hours to pass over several hundred kilometres, aggregation of wind capacity turns the sudden interruption of power into a multi-hour downward ramp.

Regarding **offshore wind power**, the ramps can be higher and occur in less time, 24% of offshore wind capacity in 40–55 minutes in Denmark have been recorded (Cutululis et al., 2011; Cutululis et al., 2013a). However, after a new controller for extreme wind speed has been installed, the extreme ramp events have been significantly reduced. Modifying the control of the individual wind turbines such that they continue producing at higher wind speeds, albeit at a reduced level, can significantly reduce the power ramping in extreme wind events and, indirectly, greatly improve the short-term forecasts of wind power, which are critical in managing these situations (Cutululis et al., 2013b). In Figure 9, the recorded power production from Horns Rev 2 wind power plant in Denmark is presented. This event occurred after the storm controller was replaced with a more advanced one (HWRT), which kept wind turbines producing power at higher wind speeds. The improved operation is shown by comparison with the power expected with the previous storm controller (HWSD). This also resulted in a significantly improved wind power forecast (Cutululis et al., 2013a). Other mitigation options for power system impacts of storms is requiring large wind power plants to operate at partial loads during storm events to prevent large ramps. The impact can also be reduced by changing the controls to prevent all turbines from shutting down during the same minute.

[1] REE direct communication
[2] Terna direct communication

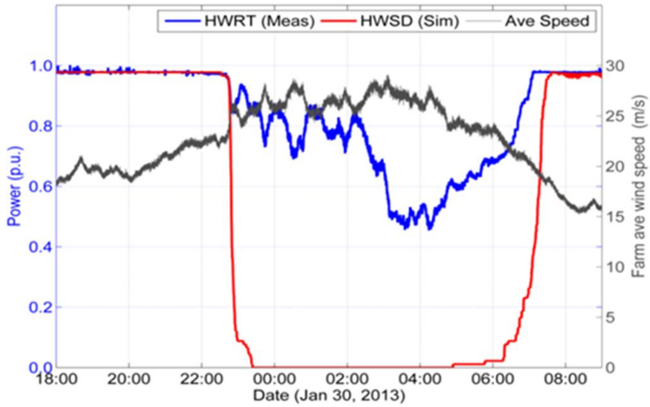


Figure 9. Wind power production during January 30th, 2013 event; Horns Rev 2 wind power plant, Denmark.

Short-term forecasts of wind power are critical in managing storm situations. Figure 10 shows as example the wind power production in Germany during the storm event Kyrill in January 2007. It is difficult to determine whether the observed decrease in power is completely based on storm cut-offs of wind turbines and wind power plants. Regarding large grid areas it is probably a mixture of storm cut-offs and damages on the transmission grid like collapses of power poles leading to disconnections of several wind power plants and therefore to an decrease of the observed power.

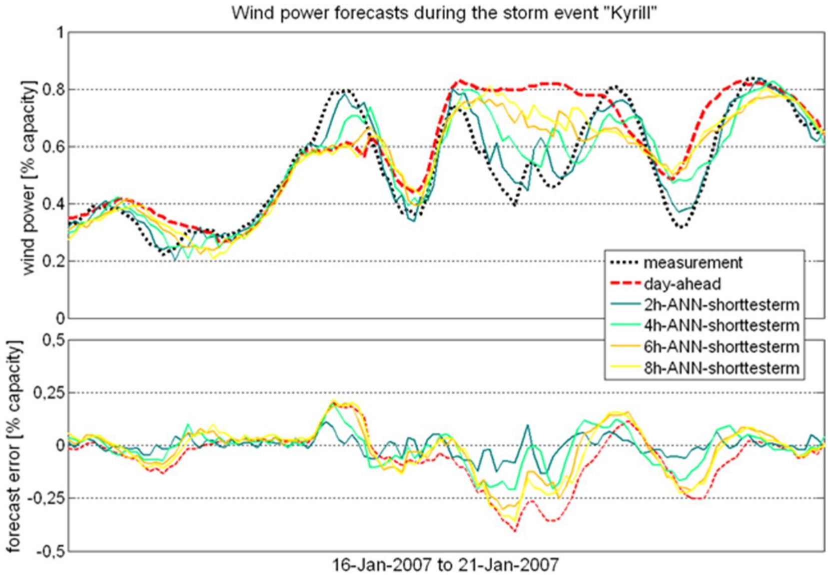


Figure 10. German wide wind power production and respective forecasts during the storm event Kyrill in January 2007.

2.2 Forecast accuracy of system wide wind power

Wind forecast accuracy improves for shorter time horizons, and for aggregated wind power plants. Figure 11 shows the final forecast accuracy in terms of the RMSE (root-mean-square-error) depending on the forecast horizon for different aggregation levels (Dobschinski, 2014). The results have been averaged over several wind power plants, wind power plant portfolios and over 20 different weather forecasts. A single wind power plant shows in average a 1h-RMSE of about 6%. An aggregation to Germany would lead to an improvement of about 80% that is about 1.2% in RMSE. Regarding day-ahead forecasts improvements up to 50% are expected by an aggregation of single wind power plants to Germany. A former analysis has shown that approximately 10–12 wind power plants spatially distributed over Germany are enough to achieve a representative forecast quality similar for all of Germany (Sensfuß et al., 2011).

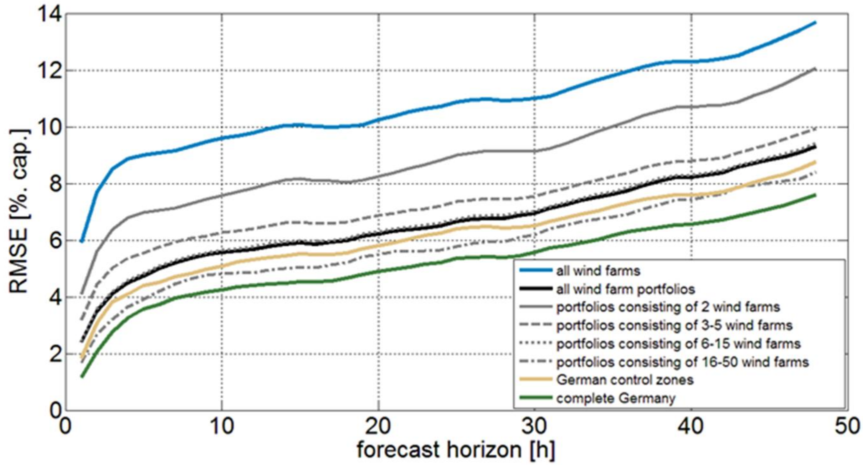


Figure 11. Forecast accuracy depending on the forecast horizon (as root-mean-square-error RMSE in percent of the installed wind power capacity). The lines present different aggregation levels ranging from single wind power plants (blue) up to complete Germany (green). The forecast accuracy has been averaged over several relevant wind power plants, wind power plant portfolios and over all 20 different weather forecasts.

The forecast accuracy further improves when aggregating several countries. For Nordic countries the average error is already quite small for the countries Denmark and Sweden that already have hundreds of sites (mean absolute error 4% and 5% and RMSE 5% and 6%, respectively), and aggregating all four countries bring the average error down to 3% (MAE) and 4% (RMSE). However, there is significant smoothing impact on the large errors (Figure 12) (Miettinen et al., 2014).

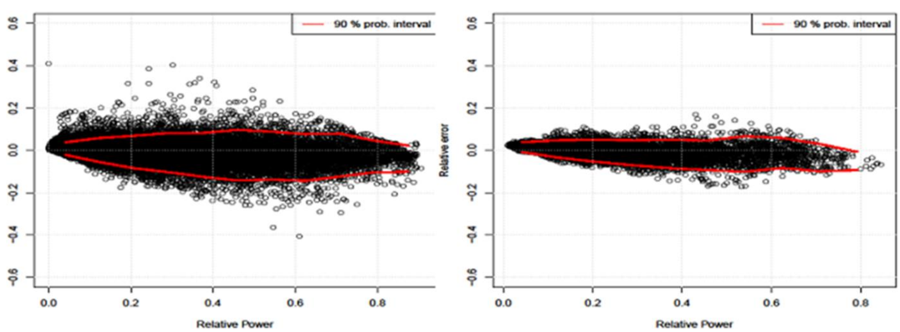


Figure 12. Forecast errors are generally higher when wind power is producing at mid-level of its installed capacity. The higher errors smooth out when aggregating larger area. Day-ahead forecast errors relative to installed capacity in Denmark (left) and Nordic countries (right). Source: Miettinen et al., 2014.

Using a combination of different weather forecasts will improve the forecast accuracy. For forecast horizons > 5 hours the combination of different weather forecasts lead to improvements of about 25% for single wind power plants and of about 35% for large-scale aggregations like Germany compared to a NWP with moderate quality. For forecast horizons < 5 hours the NPW quality becomes less important. At a lead time of 1 hour single wind power plant forecasts have an average RMSE of about 6% and Germany of about 1.2% (Dobschinski, 2014).

The **dependency between variability and predictability** could be used to standardize the forecast quality and to allow a fair comparison of forecasts covering different time periods and having different aggregation levels. Having knowledge of the characteristics of the wind power feed-in and of the available weather forecast would also allow an estimation of the forecast quality in advance. The quality of a weather model can depend strongly on special regions, so data from a small region cannot be used for stating the accuracy of a weather model. A high spatial resolution of the NWP grid with low variability in the wind speed forecast seems to be beneficial for wind power forecasting purposes. Dobschinski (2014) found a close to linear dependency between predictability and variability (Figure 13). The RMSE is based on forecast horizons of 5 to 30 hours and a NWP with moderate quality.

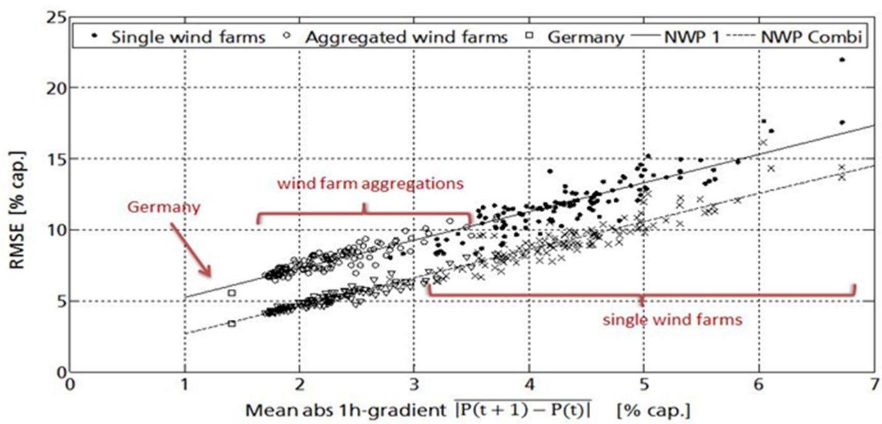


Figure 13. Dependency between forecast errors of single wind power plants, wind power plant aggregations and total Germany and the variability of the respective measurements in terms of the mean absolute 1h-gradients. The results are based on a single NWP wind power forecast with lead times of 5 to 30 hours and on a combination of different NWP.

Using old data for future forecast errors would overestimate errors. With respect to smoothing effects a further large-scale expansion of wind power installations would lead to smaller variability (in percent of the installed power) and hence to a reduced forecast error as shown in Figure 13. Moreover weather and weather-to-power transformation models will further improve which has to be considered when estimating the future forecast errors as input for integration studies.

Day-ahead and hour-ahead wind power forecast errors seen in operating practice have been studied in seven countries: US, Finland, Spain, Portugal, Sweden, Denmark, Ireland and Germany (Zhang et al., 2013). The distribution of forecast errors was shown to be poorly represented by the normal distribution often assumed in wind integration studies. The distributions were found to be more leptokurtic, with an important distinction being the heavier tails seen in the operational forecast error distributions. An example from Spain is shown in Figure 14.

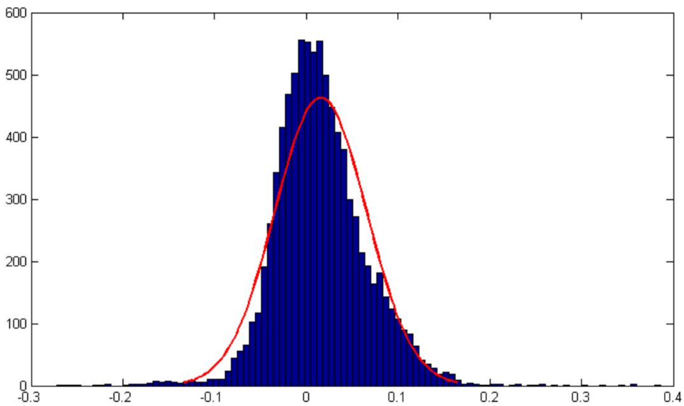


Figure 14. Histogram of the normalized day-ahead forecast errors for the Spanish system.

Extreme errors that are not represented by normal distribution can have a large economic impact on integration planning studies and system operations. We recommend that future integration studies use representative wind power forecasting error distributions to guide the process instead of making the normal distribution assumption. In this study, the hyperbolic distribution was found to better represent the entire wind power forecasting error distribution. Further investigation is planned on the significance of the differences found in the country-to-country variations of wind power forecasting error distributions, due to geographic features, forecasting methods, model input parameters, and long-term wind resource quality. Additional work disaggregating forecast error distributions based on time of day and prevailing weather patterns to extract more useful information for system operations as presented in (Zhang et al., 2013).

For the planned massive development of wind power by 2030, the **very short term forecast error** may become crucial for the system stability. According to initial studies the 15 minute wind power ramps can affect the primary reserve requirements (Cutululis, 2013b; Cutululis, 2014a).

Ramp forecasting may become important at higher shares of wind power. Improved forecasting including rapid refresh update cycle in the NWP and various configurations of the underlying weather model increased the accuracy of ramp forecasts during most months of the year in a US study. Ramp forecast performance also depended somewhat on the ramp definition that was utilized regarding ramp magnitude, direction, duration, and change rates (Hodge et al., 2014). Within the German research project RAVE Grid integration a method has been developed that allows a forecasting of time periods with high wind power fluctuations that are crucial for grid security aspects (von Bremen et al., 2012). Understanding the synoptic weather regimes in triggering a ramp-up or ramp-down event has the potential to significantly increase the security of the operation of power systems, and together with dynamic allocation of reserves can reduce the overall cost of operation of power systems. In Portugal, six weather regimes were identified to be strongly related with the occurrence of severe wind power ramps (Couto et al., 2014). During the period presented in Figure 15 large deviations between the observed and forecasted wind power production were experienced. The weather regime sequences detected in the diagnostic tool show how wind power ramp events would be expected to occur at these times. This can provide valuable information for the TSO helping to fulfil both reserve levels and adequate ramp rate capacity. A tool for automatic detection of ramps in wind generation was developed together with a methodology to alert on likely wind power ramps based on weather patterns (Couto et al., 2014; Scholz, 2014; Lopes et al., 2012).

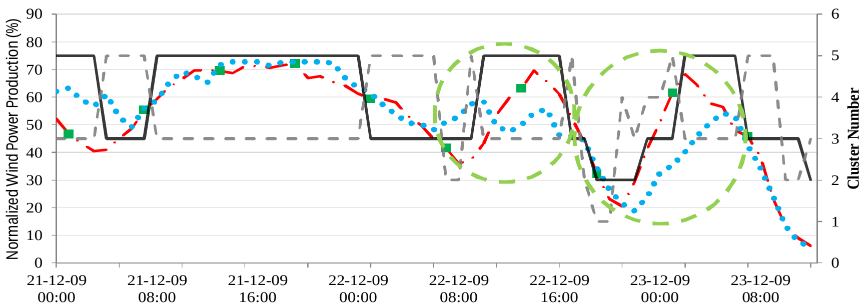


Figure 15. Example of weather pattern classification. The solid line represents the dominant weather regime; the dashed line represents the secondary weather regime; the dotted blue line represents the Portuguese TSO forecast wind power updated each 6-hr.; and the dash-dot red line the observed wind power production. The green single square points represent the initialization of a new NWP simulation. The circles highlight the periods where the methodology developed provide useful information.

3. Planning grid adequacy

This chapter lists results from studies looking at impacts of wind power on grid reinforcements.

3.1 Wind power impacts on transmission planning

Grid reinforcement costs from national studies have been published before as a summary graph (Holttinen et al., 2009). However, not many studies report the costs, and indeed the costs usually should not be allocated fully to wind power as transmission lines in most cases will be used for multiple purposes. In previous studies the effort to allocate the costs between different needs was only made in Portugal. In the European TSOs combined effort for ten year network development plans (TYNDP) estimates on allocation are depicted on general level, as share of grid that will be needed for renewables/markets/security (Figure 16). There have been several offshore grid studies in Northern Europe in recent years, summarised in Section 3.2.

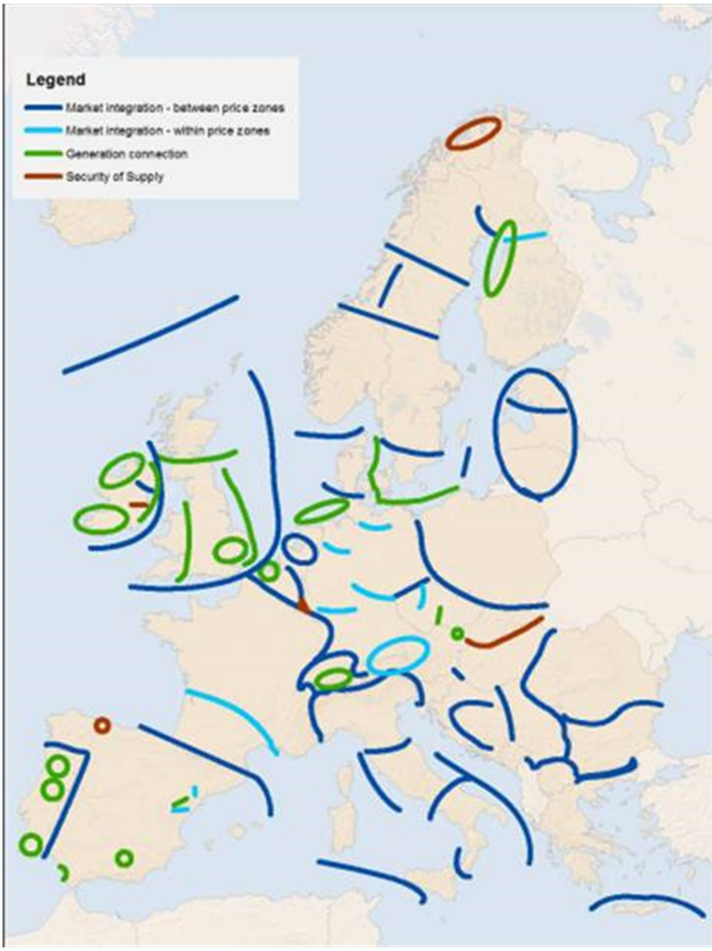


Figure 16. Main causes of transmission needs in Europe (Source: ENTSO-E, 2014).

3.1.1 National studies

US Minnesota MRITS: Midcontinent Independent System Operator (MISO) system was simulated with load flow, UCED and dynamic simulations, adding wind and solar generation to supply up to 40% of Minnesota's annual electricity needs (8 GW wind and 4.5 GW solar) and foreseen amounts of wind and solar in neighbouring MISO North/Central states (up to 38 GW wind and 6 GW solar). For this Scenario 1, a total of 54 transmission mitigations were added to accommodate the increased wind and solar generation (Figure 17). These mitigations included transmission line upgrades, transformer additions/replacements, and changes to substation terminal equipment, with a total estimated cost of $373M. No new transmission lines were required. For Scenario 2, a total of 17,245 MW of new wind/solar generation was added to increase Minnesota renewable energy penetration to 50% and MISO renewable energy penetration to 25%. A total of 9 new transmission lines and 30 transmission upgrades were added to the Scenario 1 transmission system, with a total estimate cost of an additional $2.6B. Note that an undetermined portion of the Scenario 2 transmission expansions and upgrades are associated with increasing MISO's renewable penetration from 15% to 25%. Note that for the development of transmission conceptual plans, the new wind and solar resources were connected to high voltage transmission buses. The actual connection processes will likely require additional plant-specific interconnection facilities for the new wind and solar plants.

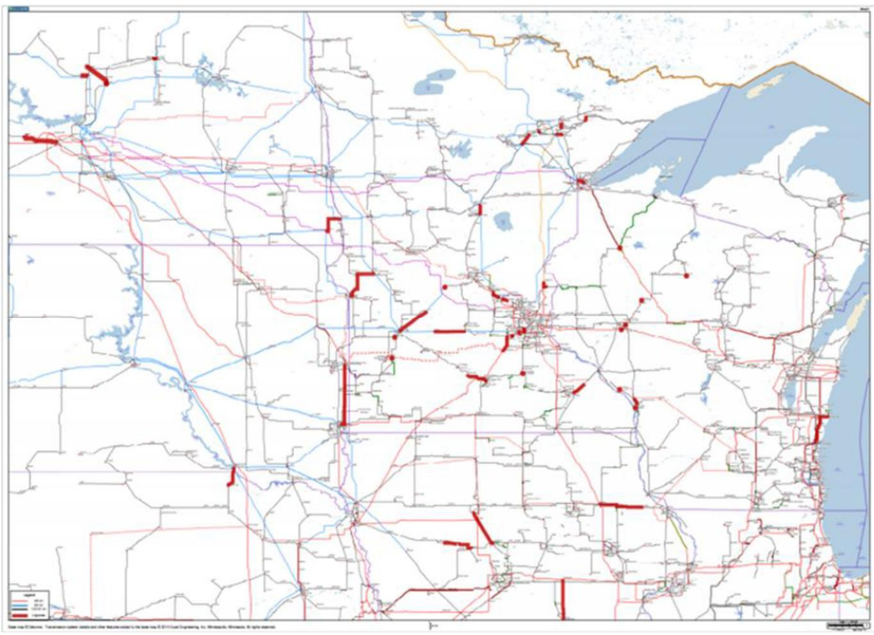


Figure 17. Transmission build out for 40% wind and solar in Minnesota (source: MRITS, 2014).

In the US, the Renewable Electricity Futures Study (REFS) (NREL, 2012) examined several scenarios of renewable energy, up to and including 90% of annual energy. Multiple scenarios were examined representing a wide range of differing assumptions regarding alternative transmission build-outs, level of flexibility in the non-renewable generation fleet, technology improvement, and renewable penetrations ranging from 30–90%. The mix of renewables included alternative levels of wind energy, solar energy, biomass, geothermal, and new hydro generation. The study also examined the transmission that would be needed to deliver the renewable energy, which included more than 50% energy from wind and solar, to load centres. The model used was not a full AC power flow, but consisted of a transportation model that was verified by a DC power flow in the production cost simulations. The conceptual transmission map is shown in Figure 18. The map shows the relative size for new transmission, and the black lines show boundaries of asynchronous interconnections in the Eastern and Western USA and Texas. This new transmission not only helped enable energy delivery, but reduced the per-unit ramping of net demand over larger areas, and enabled access to additional resources. Both of these help reduce overall balancing needs and provide additional response capability.

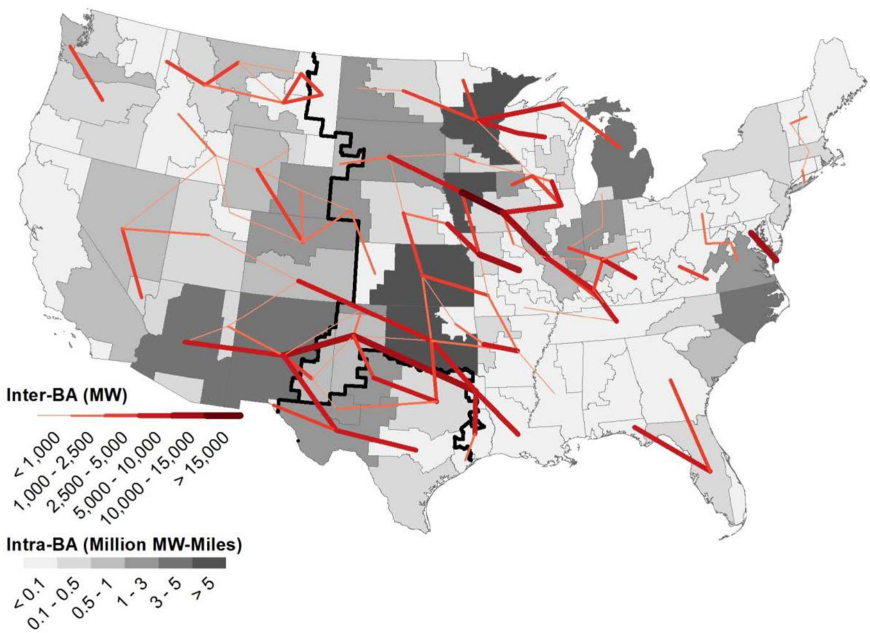


Figure 18. Conceptual transmission map from REF Study.

In Sweden a TSO study (SvK, 2013b) investigated the need of investments in the national transmission system. The need depends on several issues such as increase of nuclear capacity, more wind power, update of older lines, market integration. The total cost for the whole upgrade program is around 60000 MSEK $\approx$ 6000 MEuro. Out of this around 17000 MSEK $\approx$ 1700 MEuro refers to new generation (wind and upgrade of nuclear). However, the transmission system consists of many linked lines so a line mainly made for production can also be used for other needs such as market integration. The study has as input a Swedish wind power scenario of 17 TWh per year (10% share of wind energy).

Norway: The necessary transmission system investments and the value of hydro power flexibility, to manage wind power variability in Northern Europe, have been studied (Twenties project: Farahmand et al., 2013 and Farahmand et al., 2015). More HVDC interconnectors between Norway and other North Sea countries are necessary to be able to utilise the full potential of hydro power generation and future pumped storage capacity in Norway. Transmission corridors connecting the Norwegian hydro power plants to the HVDC interconnectors should be expanded. Figure 19 illustrates the geographical distribution of the potential hydro power stations in southern Norway according to scenarios proposed by (Solvang et al., 2012). Solid red arrows in the figure indicate possible routes for HVDC cable links, connecting to power stations, which are located close to the sea or fjords, without reinforcement of the onshore AC transmission grid in Norway. Strategic placement of the HVDC converter stations can significantly reduce the investment needs for the onshore AC grid, but due to redundancy and reliability concerns, these grid upgrades cannot be fully avoided. The dashed lines indicate parts of the onshore grid in Norway that need to be upgraded.

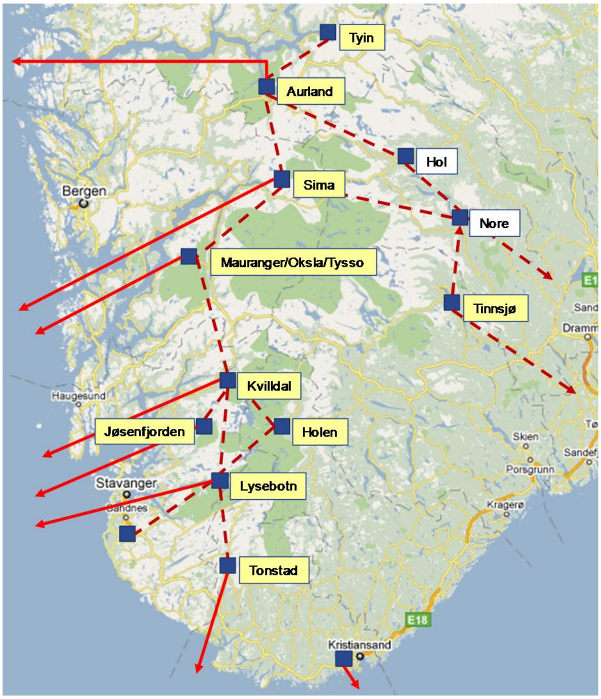
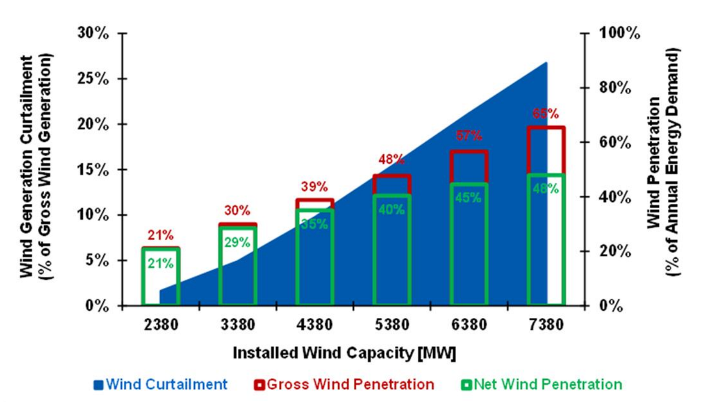


Figure 19. Interconnections needed to enable flexibility of Norwegian hydro power to be used for increased balancing needs of wind power around the North Sea (Solvang et al., 2012).

China: The accommodation capacity in Northwest China is not overall sufficient for the huge plans of wind power in the area, based on system production simulation. By 2015, more than 40% of the wind power will be transmitted inter-regionally to Eastern and Central China. The inter-regional accommodation ratio will increase to over 50%. Considering the boundary conditions such as solar power usage ratio 95% and 3GW power flow from Xinjiang to Northwest power grids, the planned solar power capacity can be basically accommodated in the province and Northwest regions up to year 2018. To improve the transmission usage of variable wind and solar resources, a hybrid mode with thermal or hydro power according to the planning transmission curve has been proposed. This can ensure the system stable operation, improve the economics and usage level of wind power, solar power, thermal power and transmission capacity. An example case of Hami-Zhengzhou ultra high DC transmission line shows how the curtailment ratio of wind and solar could be limited within 5% while keeping the price of hybrid electricity much lower than that of local thermal power benchmark price in Henan province.

In Italy the new connection between Sicily and the rest of the network will allow a better exploitation of wind source reducing the curtailment of wind generation. Curtailed wind production increases with increasing wind power both with and without the new reinforcement with the mainland (new 400 kV link "Sorgente – Rizziconi"): in the first case up to 1 TWh/year (in scenario W6), while in the second one up to 3.8 TWh/year (in scenario W6). Curtailments are due to the (in)flexibility of power plants (minimum stable operation of thermal generating units in low load conditions), the constraints in the operating reserve margins and the inadequacy of the cross-border lines (limitations in transfer capacity among the areas). Wind curtailment with about 7.4 GW of wind installed capacity (the peak load in Sicily is around 3.3 GW), allows a real wind penetration of 48% of the annual energy demand, against a potential wind penetration of 65% Figure 20), reducing curtailments with up to 2.8 TWh/year in scenario W6. In the analysed network, the flexibility of the generation fleet is the main constraint to increase the wind penetration in the analysed area.



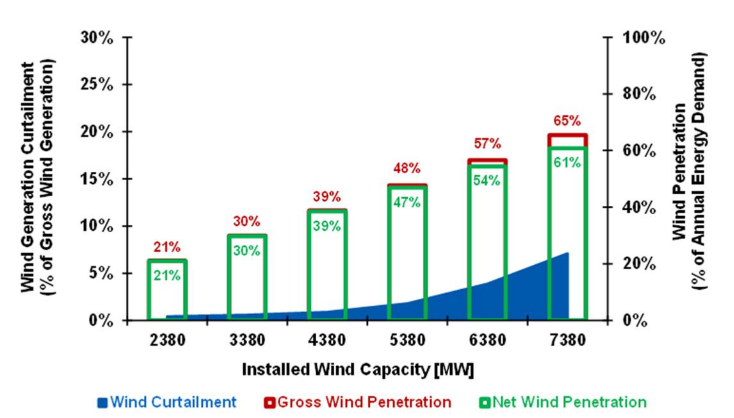


Figure 20. The development of exchange capacity with Sicily (new project Sicily Mainland) will reduce the curtailed wind generation (maximum curtailment equal to 7.1% in the analysed scenarios) and the gap between the real (net) and potential (gross) wind penetrations.

In Portugal the location and size of FACTS devices was studied, to leverage voltage during fault events, enabling non-fault-ride-through (FRT) compliant wind power plants remaining connected to the grid and consequently avoiding a massive disconnection that could lead to system instability. The obtained results demonstrate that STATCOM devices are effective solutions to provide voltage support during network faults and avoid under voltage wind power plant tripping. The final solutions that were obtained are demonstrated to be robust in several operational scenarios and for the most severe grid faults. However, the increase of wind power plants being FRT compliant to a value between 60 and 65% will make possible to meet all the defined security criteria without the need of other type of additional measures. So, wind power plant retrofit for the achievement of FRT capabilities may also be a solution to be investigated (Barbeiro et al., 2015).

In the Netherlands the impact of failures in the offshore network on the reliability of onshore transmission networks has been studied. Key question is whether the offshore network should be n-1 redundant, like the onshore transmission network. In earlier research, it was found that redundancy in offshore networks may not be an economical solution, especially when looking from a producer point-of-view: the costs of offshore redundancy are not covered by the reduction in not supplied wind energy (Tuinema et al., 2010). From a Transmission System Operator (TSO) point-of-view however, some kind of redundancy is needed to maintain a high level of security of supply. The severity of various causes of power imbalance were studied and compared in (Tuinema et al., 2015). This study revealed that power outages caused by failures of the offshore network are less frequent than large wind prediction errors. In the power system, there must be enough reserve generation to deal with wind prediction errors. If the onshore generation system is strong enough to cope with wind prediction errors, onshore reserve generation can serve as redundancy for the offshore network to a certain extent. In future systems energy storage and demand side response can be alternatives for offshore network redundancy.

3.2 European offshore grids

Studies of European renewable electricity development have estimated required transmission capacities, in some cases indicating a rate of construction twice the historical rate (Hewicker et al., 2011). Visions are developing for an offshore grid facilitating the exploitation of the offshore wind resource and allowing increased trade between North Sea countries (Woyte et al., 2008; De Decker et al., 2011). A North Sea offshore grid is high on the European political agenda, as it is one out of the 12 corridors defined in the infrastructure regulation of the European Union EC 347/2013 (Orths et al., 2012; European Commission, 2014).

Long term strategies for the development of offshore grids and onshore grid expansion should be done in a coordinated way to ensure optimal developments. This has been the conclusion from several larger trans-national offshore grid studies (EU Twenties project and Netherlands: North-Sea Transnational Grid research project). Onshore and offshore network extensions must be planned together in order to fully take advantage of the operational benefits of an offshore grid, like less CO_2 emissions, transnational power exchange and advanced control during disturbances (NSCOGI, 2012).

In a more coordinated grid rollout, more offshore hubs are needed and fewer cables are connected to shore, but they have a higher rating (PWC et al., 2014). The net effect was estimated to a higher infrastructure investment cost of EUR 4.9 to 10.3 billion for coordinated network development. However, this investment pays for itself through the techno-economical, environmental, and strategic benefits that are enabled in this coordinated network development. The annual savings in 2030 including costs of losses, CO_2 emissions and generation savings were estimated to EUR 1.5 to 5.1 billion for coordinated offshore grid development.

These monetized benefits would make the coordinated offshore grid profitable in all scenarios. The study finds that when states also coordinate their reserve capacity, an additional EUR 3.4 to 7.8 billion generation investment cost reduction can be obtained.

ENTSO-E concluded that the possibility to design an efficient final optimal grid infrastructure for 2050 a priori is challenged by the highly dynamic and changing environment regarding offshore generation level and future regulatory framework. Thus any potential offshore grid would need to be built in a modular way. Every step has an impact on both existing as well as future projects which necessitates careful continuous planning creating a minimum level of (financial) certainty for TSO's, suppliers, wind-developers and other stakeholders leading to positive business cases for each of the involved parties.

In UK, the benefits of alternative policy approaches associated with different levels of coordination and EU market integration were examined (Strbac et al., 2014). Increasing levels of market integration ranged from limited (energy neutral and self-secure) to a fully integrated EU electricity market. The significance of a strategic versus present incremental approach to integrating North Seas offshore wind will depend on the level of wind generation deployed. It is also important to see how strategic infrastructure investment decisions can deliver sufficient flexibility to accommodate various future wind development scenarios. This means keeping options open for multiple network designs that are not overly constrained by the network design selected in earlier years. The extent to which strategic infrastructure investment decisions could accommodate various future wind development scenarios demonstrated that it is better to marginally over-invest and run the risk of stranded assets than under-invest and considerably constrain the available wind energy output. In other words the potential regret associated with 'over-building' the grid in expectation of high levels of deployment is much lower than the regret associated with 'under-building' the grid on the basis of overly conservative deployment expectations.

3.2.1 Impacts on market operation

Significant expansion of transmission capacities in reality can encounter technical, regulatory, social and/or legal obstacles. From an economic viewpoint, developing transnational transmission infrastructure requires a massive investment (NSCOGI, 2012). They will have significant impact on the market operation of different countries.

It has been observed that North Sea countries benefit unequally from the offshore grid. Being a winner or a loser depends on various economic, technical and geographical characteristics of the region such as market liquidity, conventional generation fleet profile and wind availability (Torbaghan et al., 2015a; Torbaghan et al., 2012). This study introduced an approximation to the HVDC power flows, with a HVDC based pricing mechanism that is consistent with the existing AC counterpart. The proposed market mechanism facilitates the integration of a multi-terminal HVDC offshore grid into the AC grid.

Existing nationally oriented support schemes also need to be amended to become applicable to cross-border projects envisioned in the North Sea. Assuming that a common feed-in premium would be introduced to support offshore wind projects, regardless of the payment basis (generation-based or capacity-based), the support premium level is the most influential factor that has to be determined adequately (Torbaghan et al., 2015b; Torbaghan et al., 2014). A too low or too high premium results in under- or over-recovery of the offshore wind investments and undermines the essential offshore wind investments that are needed to fully exploit the offshore wind potential. This ultimately results in social welfare loss and higher costs for end users. In addition to the premium level, the installed wind capacities, design of the offshore grid and social welfare distribution are observed to be sensitive to the maximum budget provisioned to be dedicated to offshore wind projects (Torbaghan et al., 2015b; Torbaghan et al. 2014).

ENTSO-E notes that a stable market and regulatory framework (e.g. RES incentives, anticipatory investment possibilities), and adequate expectations about future market price differences are key factors in creating a stimulating environment for suppliers and research institutions to invest in further investigations, regarding e.g. the system behaviour of meshed DC systems and a parallel operation of AC and DC systems. The regulatory framework should support parties collaborating to develop hybrid solutions or multilateral interconnections. This would among others need the timing of offshore wind power plants and interconnectors to be closely aligned and coordinated. Currently these are mostly planned independently from each other and by different parties, as they follow different objectives. In any case, each project needs to demonstrate that the benefits of the selected solution outweigh its costs.

3.2.2 Technical issues

The technical issues have been well defined and addressed in the literature (Beerten, 2013; ENTSO-E, 2011).

The North-Sea Transnational Grid research project in **the Netherlands** http://www.nstg-project.nl/) used a round-the-year approach which combines market simulations (hourly resolution with wind and PV time series) with load flow calculations. Topology of a transnational offshore grid based on VSC-HVDC can significantly influence the power flows and dynamics of the entire system. Dynamics were studied by selecting a high-wind, low-inertia case and incorporating a dynamic multi-terminal VSC-HVDC model into a stability-type simulation. The main recommendation is to explicitly include the offshore part of the network into both market and stability grid integration analysis.

The **North Seas Countries' Offshore Grid initiative (NSCOGI),** which is a cooperation between 10 countries' energy ministries, the EC, national regulators and national TSOs, published their grid integration study in 2012 (NSCOGI, 2012). In this study a radial versus meshed design for offshore grid was analysed in combining connection of offshore wind power plants and interconnections. Both, the radial and meshed approach result in rather similar associated production cost savings, although there are significant differences in how they were achieved, e.g. the routing of some major flows across the region shifted between both designs, resulting in different levels of investment for the single countries. The results summed up to roughly 9,000 km of new lines to be built at the cost in the order of 30bn€ on top of the 77bn€ already spent in the period 2012–2020 to reach the 2020 "start grid" identified in ENTSO-E's ten-year-network-development-plan TYNDP2012 edition. Also market benefits, import/ export positions and CO_2 emissions were similar for the scenarios. The similarity in results can be explained by the relatively small volume of offshore renewable energy assumed to be installed between by 2030 in this scenario (55 GW), based on the 10 governments' best available input data in summer 2011. A sensitivity analysis ("RES+ scenario"), roughly doubling the offshore wind volume up to 117 GW demonstrated increased benefits for a meshed design (i.e. increasing the use of hybrid projects and point-to-point interconnections). "Benefits" is here used in terms of saved investment costs only, as the socio-economic welfare had not been evaluated in the NSCOGI grid study due to lack of time.

Additionally, the study noted that high volumes of offshore wind capacity are not expected before 2020, and that there remains significant uncertainty on potential volumes for 2030. The precedent "Offshore Transmission Technology Report" (ENTSO-E, 2011), evaluating the technology assumptions for the 2030 grid study concluded that assets will be available in the market when needed[3]. Therefore, since 2013 the primary focus of NSCOGI shifted to the regulatory/ market and to the permit work stream. (Orths et al., 2013).

ENTSO-E (European Network of Transmission System Operators – Electricity) Ten-Year-Network-Development Plan (TYNDP) of December 2014. (ENTSO-E, 2014) includes a summarizing view of the projects crossing the Northern seas, which are further elaborated in the regional investment plan of the North Sea region for a 2030 time horizon. A special chapter compares the NSCOGI Grid study and the TYNDP results. The overall NSCOGI input data for demand and renewable energy sources were well between the ENTSO-E "grey" Visions 1, 2 and the "green" Visions 3, 4. The assumptions on thermal units left in the system differed, with NSCOGI ministries' estimates being above the ENTSO-E visions. On a country base these statements might differ. Finally all studies come to rather similar general conclusions:

- Adding infrastructure is beneficial for the region, thus cooperation among countries and among stakeholders is key.
- Offshore solutions will be a combination of both, "radial" and "meshed" structures, using both, AC and DC technology.
- The choice should be made on a case-by-case basis, always on the basis of technical and economic parameters (using a cost benefit analysis).
- Offshore infrastructure in the Northern Seas region will develop in a modular way connecting the four regional synchronous areas closer to each other and

[3] NSCOGI Grid study and HVDC Technology report are both available here: http://www.benelux.int/NSCOGI/

connecting increasing amounts of offshore wind power plants. Thus, a large-scale offshore interconnected grid may emerge in the future, developing from the convergence of locally-coordinated solutions.

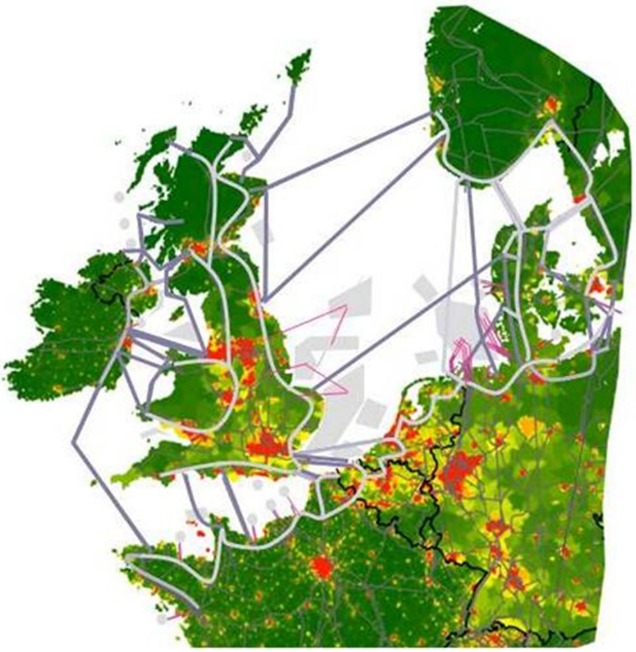


Figure 21. North Seas Offshore Grid Infrastructure 2030 according to ENTSO-E's European Ten Year Network Development Plan TYNDP (ENTSO-E, 2014). (Light grey: existing connections, dark grey: new connections, grey areas: wind exploitation areas.)

ENTSO-E advocates naming the concept more generally an "offshore grid infrastructure" instead of "radial versus meshed", as there have been different definitions using the same word. In such an offshore grid infrastructure all technical solutions, be it AC or DC, for either connecting offshore wind or interconnecting countries (or both in hybrid projects), provide possibilities to integrate the regions' four synchronous areas and offshore wind power plants as well. The realization of this infrastructure has already started by existing projects, which all will be part of the future offshore grid infrastructure.

When combining the 19 identified regional projects from the TYNDP, which cross the Northern Seas, an overall picture emerges showing a strong step towards an integrated Northern European offshore grid infrastructure and enable the integration of wind generation (on- and offshore) and increase the interconnection level between the regions' synchronous areas and neighbouring countries as well.

The interconnections crossing the Northern Seas waters are completed with onshore reinforcements and represent more than 10000 km of new DC subsea cables by 2030 in the area. The scheme highlights both, new and existing assets (both offshore and onshore). Four of these TYNDP projects combine both generation connection and interconnection capability between countries in the North Seas and constitute so called “hybrid projects”: In general, such a design appears the exception, where the rule is on the one hand the connection of offshore wind power plants to shore (through dedicated AC or DC offshore hubs), and on the other hand a point to point interconnection to connect countries. Such a separated design still saves costs, as it often appears cheaper to build and operate the large AC/DC converter station required by interconnection onshore instead of offshore. Currently offshore platforms are still very expensive, limiting offshore opportunities, thus much system integration is provided by the onshore systems behind the point-to-point interconnections; the “meshing” is done onshore. The overall scheme is expected to save between € 1.0 billion per year and € 4.1 billions per year depending on the Visions, at the cost of about € 17–22 billions.

4. Ensuring long term reliability and security of supply

Wind power will provide more capacity and thus add to the reliability of the power system. However, the benefits of added capacity vary depending on how much wind resource is available during times of peak loads. In most countries this is not a critical question in the start of deployment, however, there is already experience from conventional power plants withdrawing from the market due to reduced operating times and full load hours to such an extent that their economics deteriorate. This will raise the question of resource (or generation) adequacy in the power system.

To assess resource (generation) adequacy, capacity value of wind power needs to be assessed. The recommended practice for capacity value calculation is based on Loss of Load Probability (LOLP), with at least 10 years of synchronous data for wind and load to capture the critical correlations there may exist in weather (Holttinen et al., 2013).

The results presented in the summary for capacity value of wind power are from the following studies, using different methodologies:

- Germany (Dena, 2005)
- Ireland (AIGS, 2008)
- Ireland (EirGrid 2015c)
- Norway (Tande & Korpås, 2006)
- Quebec (Bernier & Sennoun, 2010)
- UK (Ilex Energy & Strbac, 2002)
- US Minnesota (EnerNex/WindLogics, 2004 and 2006)
- US New York (GE Energy, 2005)
- US California (Shiu et al., 2006)
- US EWITS study (EWITS, 2010)
- Finland (Kiviluoma & Helistö, 2014)
- US Minnesota MRITS (MRITS, 2014).

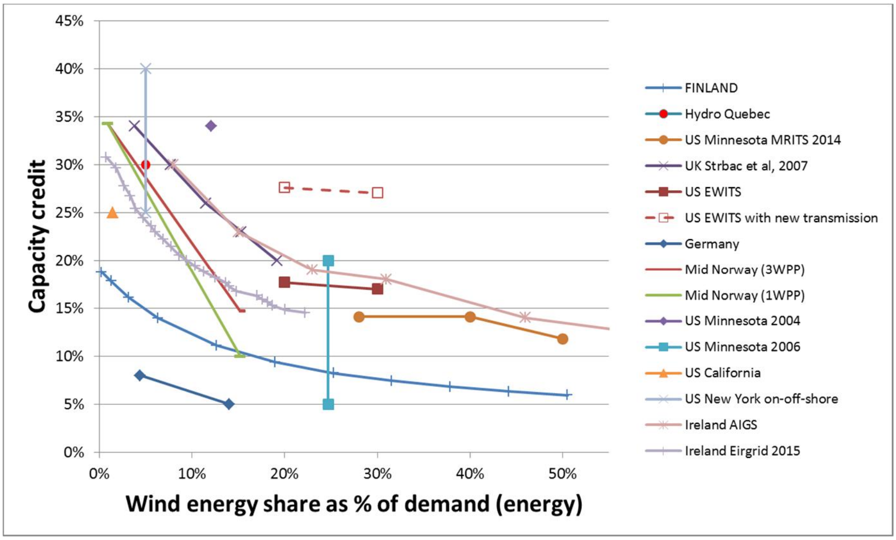


Figure 22. Capacity value (capacity credit) of wind power. Comparison of results from different analyses.

In Ireland Eirgrid published updated information on capacity value of wind power in their capacity statement (Eirgrid, 2015c). Results show the capacity value of wind power decreasing from 30% capacity value of wind power at 10% wind share to less than 15% capacity value at 50% wind share of capacity. This has been converted to share of electrical energy in Figure 22.

In Finland VTT made a report for the Finnish Energy Market authority on the capacity adequacy of the Finnish power system (Kiviluoma & Helistö, 2014). This included the impact of wind power and enabled to make a capacity adequacy calculation for different shares of wind power. There were 9.5 years of historical time series available. The results are visible in Figure 22, which shows a steady decline in wind power capacity credit with increasing share.

Due to the rarity of peak load events and the potentially complex correlations between wind power generation and electricity demand, one would like to have data from very many years. Consequently the data was extended by using 33 years of meteorological model data (NASA/Merra) to recreate electricity consumption and wind power generation time series for the longer time period. The results demonstrate that even using decades of data will leave considerable uncertainty in the estimate for the wind power capacity value. (Milligan et al., 2016.)

In US, Minnesota, MRITS study needed a capacity value for wind and solar in order to perform the resource forecasting for capacity expansion. A currently developed MISO process was utilized to determine what capacity value to use for the MRITS study. The resulting capacity value values were: Baseline and 40% share of wind and solar: Wind 14.1% For 50% share of wind and solar: Wind 11.8% (MRITS, 2014).

In Italy probabilistic methods are applied to assess the power system adequacy in presence of wind generation. This allows estimating the impact of RES generation in the classical risk indexes (EENS, LOLE and LOLP) as well as the risk of wind generation curtailment. An example of this is a detailed study for Sicily interconnected with mainland. Several wind penetration levels were examined, from a relatively low level (2380 MW, 21% share – scenario W1), up to the maximum theoretical wind potential in the island (7380 MW, 65% share – scenario W6). The peak load in Sicily is around 3300 MW. Wind power will increase system reliability, highlighted by the reduction of the risk indexes, since a share of this capacity contributes to the improvement of generation adequacy (Clerici et al., 2015). The amount of equivalent conventional power plant capacity that can be replaced by wind power, without decreasing the level of the security of supply for the power system was estimated to be 41.7% for the 100 MW wind power plant.

Since the recommendations from Task 25 (Holttinen et al., 2013) and IEEE Wind Capacity Value Task Force (Keane et al., 2011) there has been new research that addresses some of the questions raised. With large amounts of wind power beginning to appear in US, there has been interest in evaluating the use of alternative metrics, such as daily loss of load expectation (LOLE), hourly loss of load expectation (LOLH), and expected unserved energy (EUE). Ibanez & Milligan (2014) showed that the relationship between these metrics is mostly log-linear, but the slope is system dependent. This suggests that individual systems have unique characteristics but once those are known it is straightforward to convert to another reliability index. The analysis also evaluated a rule-of-thumb process in use in the Western USA and found that it overestimated solar capacity value in most locations and did not recognize the variation in wind capacity value that ranged from 5–30% of rated capacity depending on the location.

5. Guaranteeing short term system reliability

Impacts of wind power on short term reliability involve potential impacts on power system stability as well as on short term balancing or supply and demand: setting the amount of operational reserves for frequency control. The impact of wind power on power system dynamics is becoming increasingly apparent with larger shares of wind power, and it will become more important are to study in wind integration studies. Wind power also has possibilities to support the grid, and this is also taken into account in more recent work. The impact of wind power on operational reserves for frequency control has been the focus of many integration studies for decades. New studies are increasingly looking at dynamic allocation of reserves.

5.1 Wind power impacts on grid stability

Wind generation, by its mere presence, does not necessarily worsen the stability of a system, but it does change its characteristics, as it is increasingly connected via power electronics interfaces. Wind power plants can also offer a promising and viable option for defence against short term voltage and frequency instability in emerging situations and through intelligent coordination of power electronic based controls, system capabilities can be enhanced.

The issues of concern for a particular system will depend on system size, wind distribution relative to the load and other generation, along with the unit commitment and network configuration (Flynn et al., 2016). System stability issues of interest are related to

- the ability to maintain generator synchronism when subject to a severe disturbance (transient, or angle, stability);
- the ability to restore steady state conditions (voltage, current, power) after being subject to a small disturbance (small-signal, or oscillatory, stability);
- the ability to maintain an acceptable voltage profile after being subjected to a small disturbance (voltage stability);
- the ability to maintain system frequency following a major imbalance between generation and load (frequency stability).

5.1.1 Transient stability

Transient stability studies examine the operation of power systems during severe fault contingencies, with times of high wind penetration being relevant here. Wind turbines can contribute to system restoration with low / high voltage ride through capabilities (Boemer et al., 2011; Gomez et al., 2007), however, the level of support provided is network sensitive.

In the USA, The Western Wind and Solar Integration Study Phase 3 examined the impacts of large disturbances on transient stability and frequency response during high wind/solar share situations in the USA Western Interconnection (NREL, 2015). Results of this work demonstrate that the transient stability can be maintained with high levels of wind and solar, provided that local issues are adequately addressed.

In Ireland frequency and dynamic stability issues at high instantaneous penetrations of wind power were identified in the TSO Facilitation of renewables studies (Eirgrid and SONI, 2010). It was estimated that transient stability issues can be mitigated for the anticipated close to 40% wind shares.

5.1.2 Voltage stability

Voltage stability relates to maintaining an acceptable voltage profile in steady-state and following a disturbance, such as an increase in load or a network fault. Voltage instability is mainly associated with an inability to meet (local) reactive power requirements, and so is dependent on the reactive power capability of generators and the reactive demand of loads, but is also influenced by implemented voltage control strategies, such as interactions with transformer tap changers. Consequently, when assessing voltage stability at high wind penetrations, the potential to utilise the reactive power capabilities of the turbines is a key determining factor.

In general, voltage stability is likely to be unaffected or enhanced by the presence of wind turbines (You et al., 2013), if the turbine reactive power control capabilities are deployed to manage voltage (Vittal et al., 2010). However, it may be appropriate, particularly in network regions where (conventional) generation has been displaced, to introduce SVCs, synchronous compensators, or similar equipment, or even to make certain generators 'must run' for voltage support reasons.

Modern wind turbines are attractive option for defence against voltage instability since they have fast reactive power control capability. However, protection strategies for voltage instabilities need to be redesigned to accommodate these capabilities (Das et al., 2013).

In EU projects TWENTIES and ReServiceS, voltage control capabilities of wind power plants were studied. Wind power plants with appropriate capabilities can support voltage control also at high voltage transmission level, if located at short electrical distance to the transmission system (TWENTIES, 2013). Frequency and voltage support will require coordination between Distribution system operators (DSOs) and Transmission system operators (TSOs) (Kiviluoma et al., 2014).

5.1.3 Frequency stability

Frequency stability challenges depend on system size, share of wind power and applied control strategies. This was first studied in smaller systems such as Ireland, but is increasingly being studied for larger areas with higher shares of wind power. With lower levels of directly connected, synchronous large rotating machines and more power-electronic devices such as wind and solar energy the inertia in the system will decrease. With lower amount of inertia there is a risk that after a failure at a large power plant (a sudden trip-off) the frequency will drop to too low level before the frequency control (primary control) has stabilized the system.

In Ireland frequency stability issues at high instantaneous penetrations of wind power was of greatest concern in the TSO Facilitation of renewables studies (Eirgrid and SONI, 2013). For a small synchronous island system the frequency stability concerns resulted in a constraint limiting the instantaneous penetration of non-synchronous sources of generation (wind power and HVDC imports) to 50% of demand plus HVDC exports. In 2015, the limit was raised to 55% on a trial basis. It was estimated that voltage and transient stability issues can be mitigated for the anticipated close to 40% wind shares, and small-signal stability was not seen as an issue. One particular concern is the ability of wind and conventional generation to remain synchronized to the system at rates of change of frequency in excess of 0.5Hz/s. EirGrid introduced two new operational constraints in November 2014: a minimum inertial constraint for sufficient inertia online at all times (20,000 MWs) and the expected rate of change of frequency (RoCoF) following a contingency event not exceeding 0.5Hz/s (EirGrid 2014; O'Sullivan et al., 2014).

In December 2015, Eirgrid published findings from a study which investigated the possible role of wind power technologies supporting frequency stability following a loss of generation event, using synthetic inertia or fast frequency response (EirGrid, 2015a). The study found that in combination with the synchronous response of conventional generation, fast frequency response from wind power plants can be effective but that the effectiveness was highly sensitive to the characteristics of the response. To be effective the response must be provided within 100ms of the event and the full response must be delivered before 200ms after the event. It was found that a total capability of at least 360 MW of fast frequency response would be required for the duration of the event. Concerns were highlighted around possible unintended adverse system issues during the frequency recovery phase which would require appropriate control systems to mitigate.

In the USA Midcontinent Independent System Operator (MISO) system was studied with 40% share of wind and solar of Minnesota's annual electricity needs and foreseen amounts of wind and solar in neighbouring MISO North/Central states. MISO is a part of the Eastern Interconnection, which has a summer peak load of approximately 600 GW, and an installed capacity of 700 GW. Dynamic simulation results indicate that there are no fundamental system-wide dynamic stability or voltage regulation issues introduced with wind and solar resources increased to achieve 40% renewable energy for Minnesota. This assumes that new wind turbine generators are a mixture of Doubly Fed Induction Generator (DFIG) and fully converter based turbines with standard controls; the new wind and utility-scale solar generation is compliant with present minimum performance requirements (i.e. they provide voltage regulation/reactive support and have zero-voltage ride through capability) and that local-area issues are addressed through normal generator interconnection requirements.

In the USA, The Western Wind and Solar Integration Study Phase 3 examined the impacts of large disturbances on transient stability and frequency response during high wind/solar share situations in the USA Western Interconnection (NREL, 2015). Response for light loads and heavy loads were examined, based on well-established cases from the Western Electricity Coordinating Council. Time periods of high and extremely high wind/solar penetrations (44 and 53% of generation) were compared to a base case representing a more modest penetration of wind and solar. The frequency response to the loss of two Palo Verde generating units (WECC's design criteria) is shown in Figure 23. In all cases, under-frequency load-shedding was avoided because the frequency nadir never hit 59.5 Hz, which would have triggered such response. However, the frequency response is clearly significant and exacerbated by the high level of wind and solar energy.

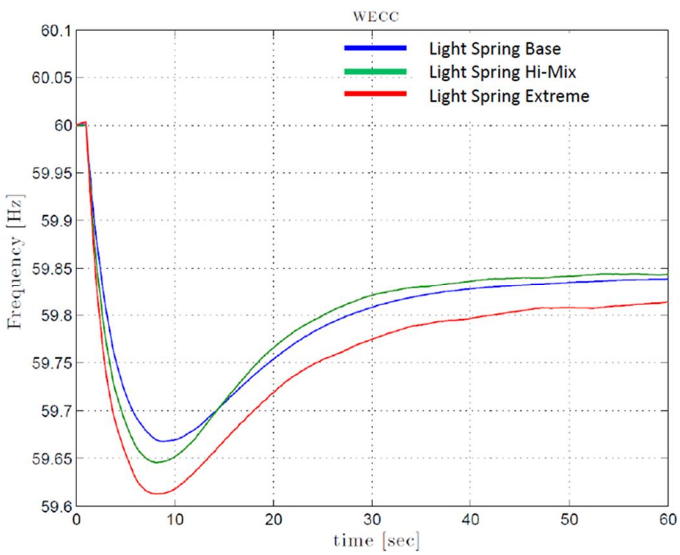


Figure 23. Frequency response to loss of two Palo Verde units under light spring system conditions, with 44% and 53% wind/solar share.

These results were compared to a case in which two types of frequency-responsive controls were added to wind power plants: simulated inertial response and active power control/governor functions both set to represent the respective settings on conventional plants. Wind power was half (27.2 GW) of installed wind and solar capacity (52.8 GW). Results comparing various cases are in Figure 24.

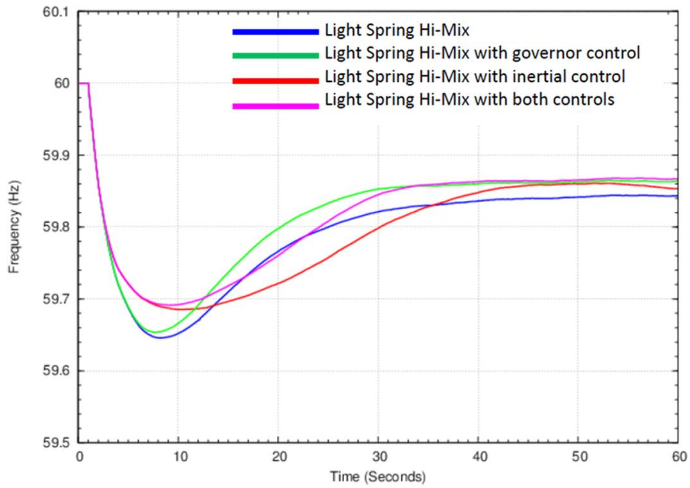


Figure 24. Frequency response to two unit trip for 44% wind/solar share of generation case with three combinations of frequency controls on wind power plants.

Results of this work demonstrate that the adequate frequency response can be achieved providing mitigating steps are taken.

In Sweden frequency stability issues due to high share of wind power have been simulated in a simplified way (SvK, 2013a). From observed frequency derivative for some trip-offs that have occurred it is possible to estimate the inertia in the system. And based on an assumption of future amount of wind power it is possible to estimate the drop in the initial frequency derivative and thereby the consequence of the same type of outage in a future system with larger amounts of wind power. The analysis led to the conclusion that 7000 MW of wind power will lead to a further frequency decrease of less than 0.07 Hz. In a low load case and an outage of 1400 MW, 7000 MW of wind power could decrease the frequency with 0.2 Hz, compared to the case with no wind power. It must be noted that Sweden is a synchronous part of the Nordic power system and in the situation illustrated in Figure 25, the Nordic consumption was 46600 MW. So 7000 MW only supplies 15% of the load in the synchronous area.

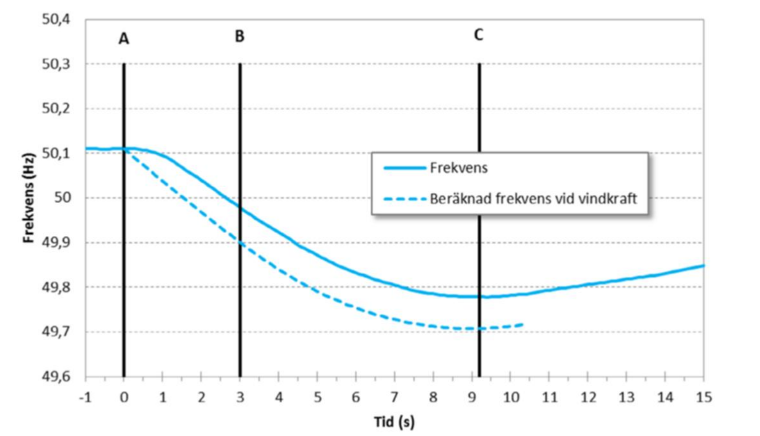


Figure 25. Frequency drop of the Nordic power system with 46600 MW load and assuming a 1400 MW trip off, with or without 7000 MW wind power (Frekvens = Frequency; Tid = Time; Beräknad frekvens vid vinkraft = Estimated frequency with wind power). Source: SvK, 2013a.

5.1.4 Offshore wind studies

Offshore wind power plants connected through VSC-HVDC can provide voltage control to the onshore AC grid, even if this would most likely be done mainly by the onshore HVDC converter, which exhibits excellent voltage control capabilities. If well designed, HVDC stations can compete with conventional machines and offer even more flexibility, particularly in under-excited scenarios (Zeni et al., 2014). The capability of the HVDC network to provide frequency control is not depending solely on the Voltage Source Converter (VSC), but also on what lies behind the DC link (Zeni et al., 2014; Silva et al., 2012). Different DC grid power sharing control approaches and the development of advanced control strategies for the provision of primary frequency regulation and fault ride-through capability from Multi-terminal HVDC connected offshore wind power plants were investigated in EU project TWENTIES (Silva et al., 2012; Silva et al., 2014).

In Denmark and Portugal, power oscillation damping capabilities from HVDC connected wind power plants has been studied. It is more demanding but its implementation should still be possible (Cutululis et al., 2014b; Zeni et al., 2014). HVDC converters can perform similarly to a conventional Power System Stabiliser (PSS) in terms of power oscillation damping (Resende et al., 2014). Coordination with offshore wind power plants is necessary to avoid possible mirroring of the oscillations in remote systems. In general, HVDC converters could substitute PSSs.

In the Netherlands, impact of large scale HVDC connected offshore wind power generation on the voltage and frequency stability of the AC system has been studied with typical grid code requirements as boundary conditions in FLOW project (http://flow-offshore.nl/page/projects#lijst_3). Limitations and trade-offs for grid code compliance of DC connected wind power plants have been assessed while quantifying the interconnected grid performance. Both point to point as well as multi-terminal HVDC connections were addressed. For the case of voltage and reactive power support during onshore AC system failures, the emphasis was placed on the onshore converter station (receiving end of the VSC-HVDC link). The additional reactive current injection during AC system failures has beneficial effects on the onshore power system voltage response and transient stability. With regard to frequency stability, the large penetration of DC connected offshore wind power generation will lead to decrease in system inertia response. The contribution of point-point HVDC connected offshore wind power plant in the frequency and inertia response is possible by implementation of additional control loops at the HVDC system level. When offshore wind power plants are connected in multi-terminal HVDC connection extended between different control areas, there is the additional option of exchanging primary reserves or synthetic inertia response between AC systems improving the interconnected AC-DC system performance.

5.2 Wind power impacts on operating reserve requirements

Operating reserves are required to ensure short-term balance between generation and demand and to ensure the stability of the power system in case of failures. These reserves have been traditionally provided by thermal and hydro power plants operating. With larger shares of wind power, the need for operating reserves will increase as wind power will bring more variability and forecast errors to the system. Power systems balance to total load and generation in a balancing area with operating reserves. Load and generation imbalances occur due to unpredicted variations. Also any variability inside the time step for dispatch (for example inside 1 hour or 15 minutes) causes imbalances in second-to-second and minute-to-minute operation of power system. Wind power imbalances will be merged with other imbalances in the power system. Operating reserve for balancing and frequency control is divided to several time-scales of response – with a very general division we can talk about automatically activated reserves (in time-scale of seconds) and manually activated reserves (in time-scale of 10 minutes or so). Usually the impact of wind power is more seen in the longer time-scale reserve.

This section summarises the experience and studies regarding allocation and use of operating reserves for systems with high shares of wind power. Wind power can also provide operating reserves – this is described in Section 6.2.3.

5.2.1 Experience on increased operating reserves due to wind power

There is already experience in managing higher shares of wind energy in power system operation. Main points are summarised as:

- **In Ireland**, operational contingency reserves are maintained to cover against the loss of the single largest in-feed which is very often the East-West interconnector. These reserves take account of the nature of the Irish system (a small island system with limited interconnection) and are driven mostly by the need to stabilise and recover system frequency after a loss of generation event. No additional reserve has been required during periods of high wind variability. However, frequency and voltage stability concerns have necessitated rules for the number of units that remain online (three units in Northern Ireland and five in the Republic of Ireland) (Söder et al., 2012). In November 2014 EirGrid also introduced two new operational constraints relating to inertia and rate of change of frequency following a disturbance.

- **Spain:** The impact of wind power to automatic fast reserve has been very small, but the overall impact to manual reserves has already been significant. Using probabilistic methods to determine the reserve requirement has shown good results but still needs testing to gain confidence in the method (Gil et al., 2010). One incident of low load and high wind has resulted in down regulation reserve to be exhausted (November 9, 2010, from 2:10 a.m. to 5:00 a.m. with 54% of the consumption fed by wind). This was resolved by TSO ordering some thermal power plants to shut down, and after that wind to be curtailed (Söder et al., 2012).

- **Portugal:** Increase in balancing is managed by existing hydro and thermal power plants, and occasionally by reducing import from Spain (Ribeiro, 2012).

- **Germany**: Surprisingly, while wind and solar capacity has tripled since 2008, balancing reserves have been reduced by 15%. This is due to the increased collaboration between the four German TSOs, reducing the overall balancing needs in Germany (Hirth and Ziegenhagen, 2015, see also Section 6.2.2 and Figure 33). However, specific situations where wind power impacts the balancing reserves can be identified, like on 30 January 2013, when the reduction of wind speed and power production was not forecasted by the day-ahead (green line upper plot) but also not by the shortest-term forecasts (blue and yellow lines) Figure 26. The resulting error was instantaneously balanced by automatically responding secondary reserve that has later been replaced by minute reserve.

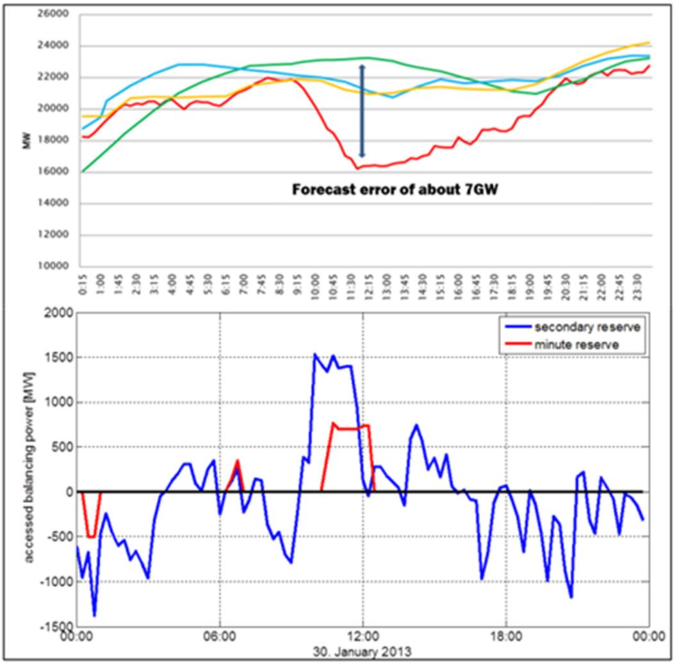


Figure 26. Wind power impacting reserve use in Germany 30 January 2013. The forecast error from shortest term forecasts was about 4 GW and the reserve use was 1.5 GW.

5.2.2 Results from estimates of increased operating reserves due to wind power

Example of how increased wind power will increase the net load variability is shown in Figure 27 (Kiviluoma et al., 2015). The hourly ramp rates are depicted for different shares of wind power, using one year of data from historical measurements of wind and load and upscaling wind power time series to reach higher shares. The graphs show extreme variability, with 1% of 0.1% highest value from the year. This will increase first quite moderately but after 10% share more steeply. The variability of wind has an impact – for the German time series with high amount of turbines and geographic dispersion the increase is not as steep as for Finland and North-West US. Also the 5 min time series seem to have less dramatic increase in variability as the hourly time series.

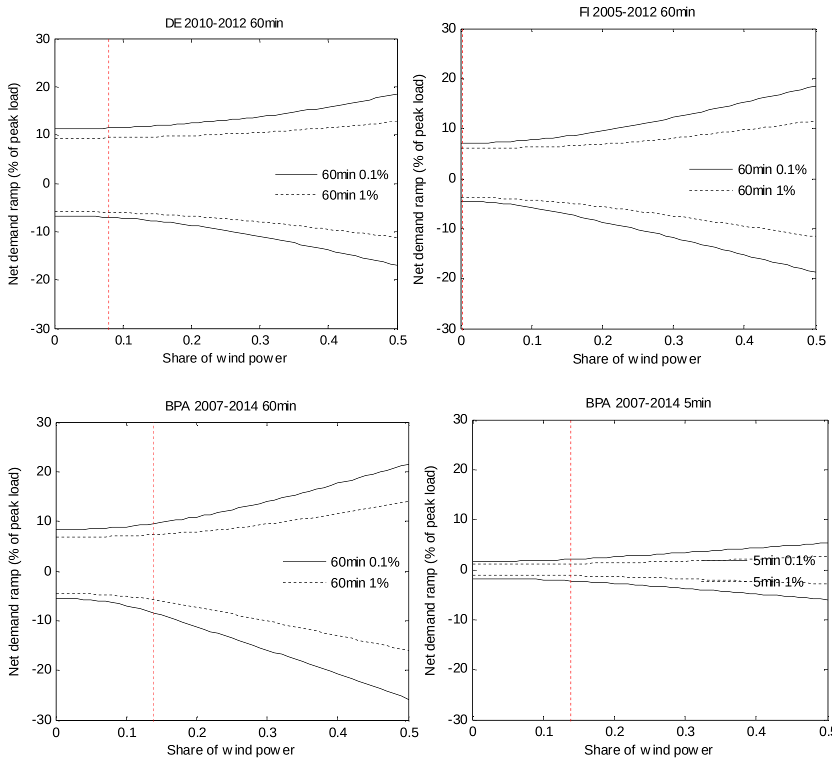


Figure 27. Selected quantiles (0.1% and 1%) of net load ramps as a function of annual energy share of wind power in Finland, Germany and BPA (in North-West US) for hourly ramps as well as BPA also for 5 minute ramps. Vertical dotted red line indicates the share of wind power in the original data set.

The updated summary from previous Task 25 summary reports is presented in Figure 28. The results presented for increase in reserve requirements due to wind power are from following studies:

- Canada/Hydro Quebec (Robitaille et al., 2012)
- Germany (Dena, 2005; Dena, 2010; Dobschinski et al., 2010)
- Ireland (AIGS, 2008, Workstream 2B)
- NL (Holttinen et al., 2012)
- Sweden (Axelsson et al., 2005).
- Nordic, Finland, Sweden, Denmark hourly variability (Holttinen et al., 2013) – average for up and down regulation needs
- UK (Strbac et al., 2007)
- US/Minnesota 2006 (EnerNex/WindLogics, 2006)
- US/New England ISO (NEWIS, 2010).

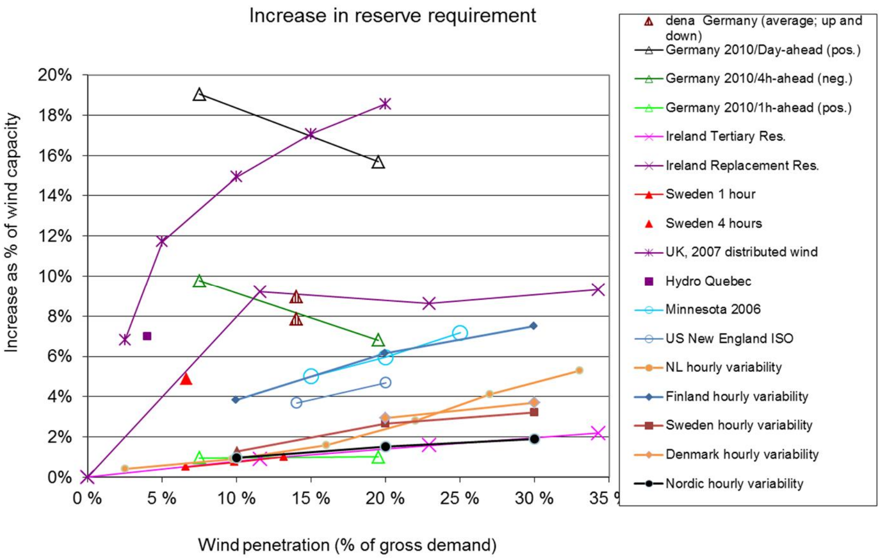


Figure 28. Summary of results from different studies for increase in reserve requirements due to wind power.

The results vary a lot, especially depending on the time horizon used for the uncertainty. Imbalances stemming from 24 hour ahead forecasts are very large (case Germany), as well as imbalances stemming from 4 hours ahead forecasts if now prediction method is used (case UK). If the reserves are dimensioned (allocated and committed) only based on hour ahead uncertainty (hourly variability), the impact on reserves is not very large. Most studies show less than 2% of installed wind power capacity at 10% wind share, 1–3% at 20% wind share and 2–5% at 30% wind share. Finland is an exception to the other studies showing about twice as large numbers. This is due to fewer sites (more variability) in the wind data, as well as the low variability of the initial load variations due to high share of stable industrial loads.

5.2.3 Dynamic reserve setting

It has been acknowledged that the balancing of the system should be done in face of its net uncertain variations. In addition, to each possible level of balancing reserve set aside in operational planning corresponds a risk that generation plus reserves will be insufficient to cover obligations at delivery time, thus forcing the operator to call on mitigating actions. Hence this risk has basically an economic value. It is thus conceptually straightforward to move to a fully dynamic, risk-based balancing of the electric system.

In the USA dynamic reserve method has been built on the observation that the variability of the wind power is a function of its output level (EWITS, 2010; Lew et al., 2013a). Figure 29 shows that the highest level of variability, as represented by the 10-minute ramps, occurs near the middle of the operating range of all wind generation in the footprint. A statistical characterization of this information yields a dynamic reserve which can be divided into regulation (less than 5 minutes) and flexibility (dispatch) Figure 30.

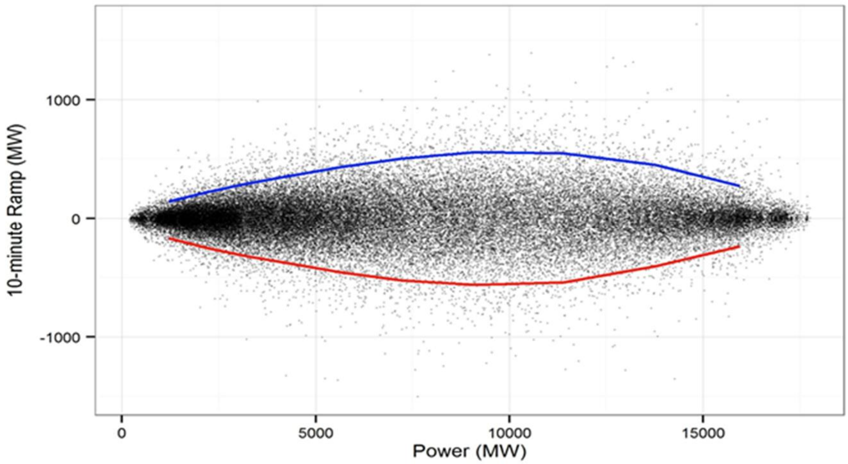


Figure 29. 10-minute wind power ramp is a function of the output level of the wind plants in the Western US area (source: Lew et al., 2013a).

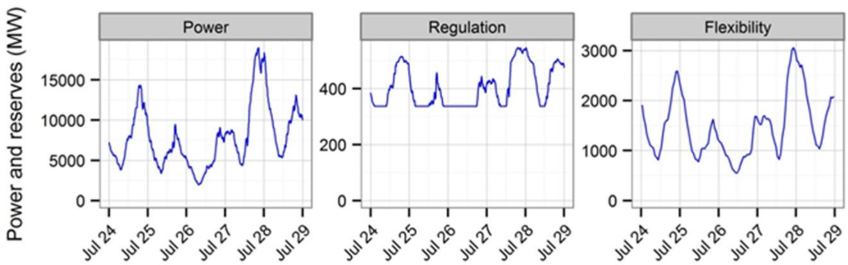


Figure 30. Dynamic regulating and flexibility reserve is a function of wind output

German research into dynamic sizing of reserves analysed all possible schedule deviations that induce a need for reserve activation, either due to forecast error or fluctuations (Jost et al., 2014). The factors that are influencing the forecast error are:

- Time of the day and day of the week
- Load and its gradient
- Temperature
- Generation of wind and PV power and their gradients
- Residual Load

The main influences on the fluctuations are:

- Load and its gradient
- Generation of wind and PV power and their gradient
- Residual load and its gradient

Probability density functions of all forecast errors and fluctuations has been analysed and it has been shown that these probability density functions are strictly speaking not stochastically independent and so cannot be convoluted. However, the convolution may be a good approach when only low and high quantiles are considered (Jost et al., 2014).

In Portugal INESC-Porto/FEUP developed a tool for setting the operating reserve in systems with high share of wind power. The results show that deterministic methods may lead to situations with either high risk or cost. The probabilistic tool was able to inform the operator about the risk of loss of load of generation surplus, leading to more accurate decisions (Bessa et al., 2012)

In **Québec, Canada**, methodological development is on-going to integrate dynamic risk-based balancing reserves into the operational tools (Menemenlis and Huneault, 2015). As a first step, these are being incorporated in the deterministic unit commitment, closely mimicking a stochastic approach using a chance constrained solution methodology. A stochastic unit commitment approach is under development to support the next step of this work, aiming at a whole system optimization based on a global objective. Operational impacts on ancillary services due to additional wind production have been addressed by simulations, and refinement of the methodologies are ongoing: From the state estimator grid configurations, SCADA data and planned peak network, simulations are run over several years at 1 minute time step, with and without additional wind, or other variable, power. The simulator takes into account all the security and regulation rules of the transmission system operator, as well as the long term planning assumptions to represent the network when all wind power plants will be installed.

6. Maximizing the value of wind power in operations

The value of wind power will be maximised when there is no need to curtail any available power, and when the impacts to other power plants in the operational time-scale are minimised. In addition to experience and results of curtailments and balancing, this section describes measures to enhance the balancing task with high shares of wind power: operational practices and markets, demand side flexibility and storages.

6.1 Curtailment of wind generation

Curtailed wind generation is one metric showing how well wind power can be accommodated by the power system. Reduction of available wind energy can be used in critical moments when there is a surplus of energy and no other means to absorb the energy by the power system. There is experience on curtailments from several countries. Wind curtailments are also often calculated from wind integration study simulations for power system dispatch, showing the challenges of wind integration (Lew et al., 2013b).

There are several possible reasons for curtailment.

- Transmission congestion, or local network constraints, is a common reason for curtailment. New wind power plants may be curtailed until adequate transmission infrastructure is commissioned (US Texas, China, Italy). If curtailments are rare events, it may be economically efficient to curtail single hours instead of expanding the network.
- System balancing can be another reason for curtailment. When wind generation is high during low loads, thermal units may be pushed down against their minimum operating constraints, especially if they have to reserve down-regulation. This may even apply to generally flexible systems such as in a hydro based region, when run of river plants running close to their minimum flow suffice to support load. In such a case, an economic decision has to be made whether to spill water or wind.
- In additions to these, limits may be placed on wind power as a non-synchronous generation to maintain frequency requirements and address stability issues, especially on small, isolated grids (Ireland), or

medium size non-synchronously interconnected systems (Quebec, Great Britain) under high instantaneous wind shares.

Experience of wind power curtailments shows that curtailments do not occur in smaller shares of 5–10% of yearly electricity consumption, if there are no severe transmission bottlenecks and wind power is dispatched first among the low marginal cost generation (Quebec; Nordic countries; Portugal). Portugal and Denmark have managed more than 20% average share of wind generation without curtailments using trade with neighbouring countries in excess wind generation situations. Denmark has managed 40% average share wind energy of total consumption in 2014 with only 0.21% of so called "market-curtailment". This means that wind power is closed by the producer (not by the TSO) as soon as market prices are negative (valid for two offshore wind power plants) or below -13 €/MWh (for other wind power plants. In Denmark the TSO can shut down wind power plants in case of faults on connection cables but this did not happen during 2014. In Québec, new power purchase agreements do contain provisions for compensation in case of curtailments, but effectively no curtailment has been imposed yet.

In Spain the curtailments were increasing after reaching 10% share of wind, but have remained at low levels after mitigation measures (but all in all at relatively low levels of below 1% of total wind generation).

In some countries substantial curtailments (10–20% of wind generation) have started occurring at lower shares of wind (China, Texas, Italy). The mitigation efforts regarding transmission build out have resulted in a reduction in curtailment rates with increasing wind power. In China, another reason for curtailments is due to surplus generation in the system during high winds, from must run units (like combined power and heat power plants operating according to heat load) and prioritised generation from fixed tariffs with guaranteed full load hours to coal power plants.

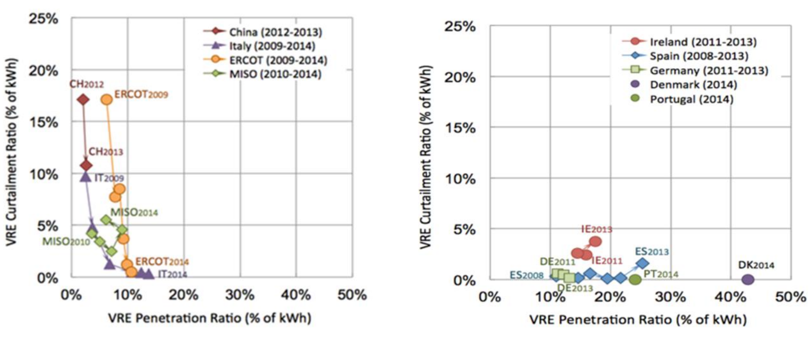


Figure 31. Curtailments of wind energy over time. Experience from Europe, US and China for transmission constrained cases (left) and countries with stronger grid (right).

For wind power producers, curtailments have been identified as a critical issue in a number of countries, especially due to the lack of curtailment rules, compensation issues, and also an expected increase of curtailments in the future (Eclareon & Öko institute, 2012).

In Minnesota, USA, the estimated future curtailments was one result of the integration study (MRITS, 2014). In the higher share wind scenario (50% share of energy) the curtailed wind power was more than 2% (Figure 32). This was caused by a mix of local congestion and system-wide minimum generation conditions.

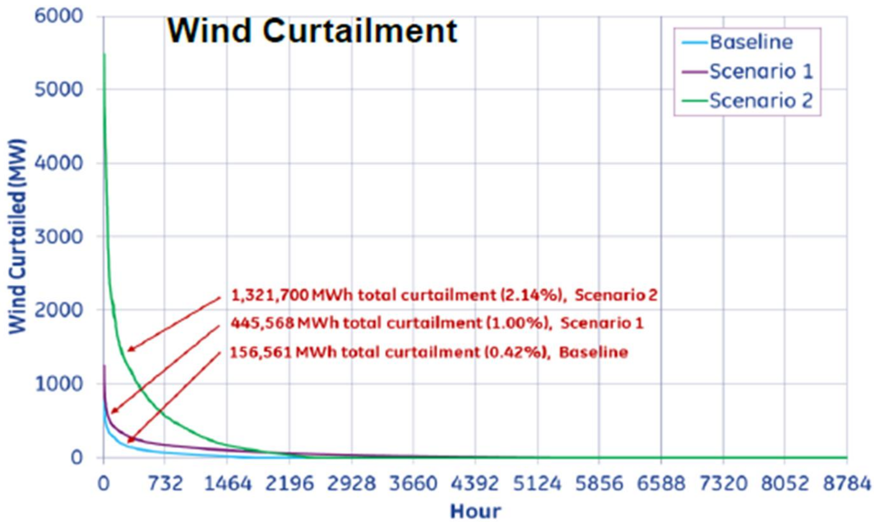


Figure 32. Wind curtailment results from Minnesota integration study simulations. Baseline has 28%, Scenario 1 has 40% and Scenario 2 has 50% share of variable renewables (wind and solar). Solar curtailment was less than 0.5%.

In Ireland the instantaneous penetration of asynchronous sources of generation is currently limited to 55% and with an annual 15% share of wind power in energy terms, this already makes curtailments necessary. It is envisaged that this limit will increase from 55% in stages to 75% by 2020. With a 40% share of wind power expected in 2020, studies show that this 75% limit will give rise to significant levels of curtailment of renewable energy. Depending on assumptions, the curtailment level is likely to be in the range of 6–8% (Mc Garrigle et al., 2013).

In Italy, the huge investments in the transmission grid in the past years have reduced the curtailments to a level of less than 1% in 2014 compared to 10% in 2009. Considering the new EU RES target in 2030, the participation of wind generation to the downward reserve seems to be necessary and will have two opposite consequences: an increase of the wind curtailment due to the participation to the downward balancing service and a reduction of the system over-generation problem (and hence the wind curtailment) because less thermal generation in service is required for creating the desired reserve margins. The amount of the generation curtailed is proportional to the real time imbalance of the system. However, relieving system over-generation situations reduces curtailments as a permanent effect. For these reasons, in general the renewable generators participation to the ancillary services market decreases the overall curtailed renewable generation. The same result was found in EU project ReServiceS simulations for Iberia (Kiviluoma et al., 2014).

6.2 Wind power impacts on balancing

Wind power will increase the variability and uncertainty that the power system experiences. The balancing task involves more ramping and cycling and more provision of short term operating reserves. Balancing cost has traditionally been the main issue that many integration studies are trying to estimate. It is becoming less of an issue in countries where experience of wind integration is cumulating. In countries where wind power is out in the markets, balancing is paid by the operators in imbalance costs (Section 6.2.4). Assessing impacts of wind power on the operation of thermal power plants (cycling costs) is described in Section 6.2.5.

6.2.1 Balancing cost estimates from integration studies

The term "balancing cost" generally refers to the increased cost of maintaining system balance that is caused by wind energy. It is important to recognize that the base, no-wind case is that the same energy must have been supplied by another resource. Thus it is not the total cost of the balancing energy that is relevant, it is instead the cost of the incremental balancing energy that is appropriate.

Integration cost studies generally attempt to capture the cost of the increased variability and uncertainty caused by wind energy, recognizing some base level of variability and uncertainty that exist even with no wind energy on the system. Methods to calculate this cost have evolved over the years, but there is currently no generally-accepted method in spite of there being general agreement that the variability and uncertainty from wind energy does have a cost. The difficulty is how to correctly calculate it. This is fundamentally a methodological issue that may not have a solution. There are three main complications involved: (1) defining a suitable "non-wind" case, (2) extracting the highly nonlinear nature of these costs, and (3) calculating wind balancing cost without doing comparable calculations for other types of generation that also impose balancing related costs (Milligan et al., 2013a; Milligan et al., 2011).

Every power plant has certain capabilities and lacks others; this is why most power systems include a portfolio of plants with different characteristics. In the USA singling out one type of power plant for certain costs or impact without applying that to all plants is not accepted practice, as ruled by the FERC (see discussion of the "comparability rule" in FERC, 1996).

Any system integration cost will significantly depend on the generation mix and level of flexibility, impacted by demand side response, characteristics of conventional plant, levels of interconnection and energy storage. Increased level of flexibility may potentially reduce system integration cost by an order of magnitude. Wind integration cost will increase with coal and gas prices, but at the same time wind power competitiveness, and value to the power system increases.

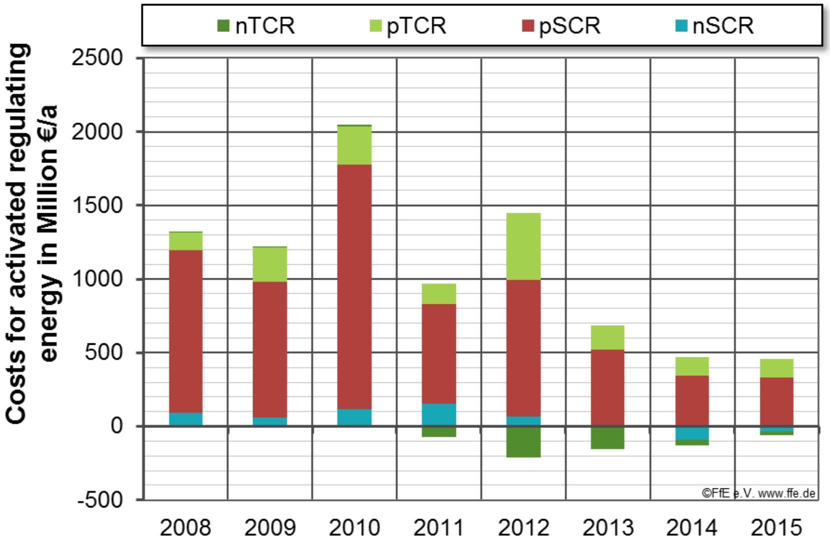
Summaries of balancing cost, relative to share of wind energy in the system, have been presented in previous Task 25 summary reports (Holttinen et al., 2013; Holttinen et al., 2009). Updates to these graphs have been few in recent years, when the balancing cost has no longer been in the focus of integration studies, and the analyses evolve towards comparing total system costs for different future scenarios, showing both operational and investment costs (AIGS, 2008; Mai et al., 2012; IEA, 2014).

6.2.2 Experience on wind power impacting balancing costs of power system

There is some experience on the actual balancing costs, recorded for the power systems with growing shares of wind power. However, other changes in system operation have a large impact on the balancing costs, as the German example shows, where the benefits of collaboration between balancing areas have outweighed the impacts of wind power.

In Italy, increasing costs in the ancillary services markets (ASM) have been observed due to the rapid increase in both wind and solar PV. This is due to TSO creating larger reserve margins than in the past to secure for increased variability and uncertainty for the non-programmable wind and PV generation as well as the reduction in the number of thermal power units dispatched in energy markets making it less likely that reserve margins are available without re-dispatching actions in the ASM. The volumes re-dispatched in the ASM and the related costs have almost doubled during the last years, exceeding 1.3 b€ in 2013, while the costs of the electricity in the day ahead market have almost reduced by one third (wind and solar shares of electricity demand 5% and 7%, from 2% and 0.2% in 2009). In order to accommodate more variable renewable generation in the power system some measures, like participation of distributed and renewable generators to ASM are under examination.

In Germany, balancing reserves have been reduced by 15%, and costs by 50% since 2008 somewhat surprisingly, while wind and solar capacity has tripled. This is due to the increased collaboration between the four German TSOs, reducing the overall balancing needs in Germany (Hirth and Ziegenhagen, 2015) (Figure 33). The impact of variable renewables on balancing of a power system was analysed to stem from three sources: the forecast errors that will increase balancing reserve requirements, the supply of balancing services by wind and solar generators; and the incentives to improve forecasting provided by imbalance charges.



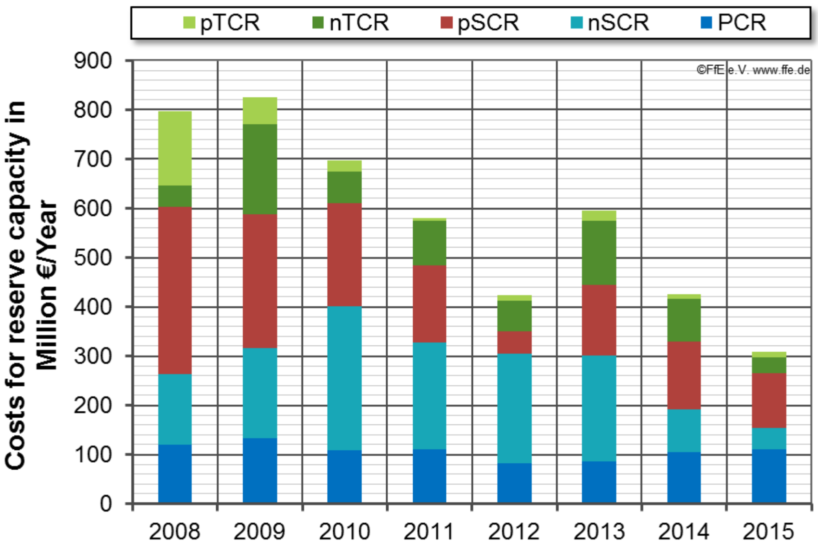


Figure 33. Cost of short term balancing in Germany – a decreasing trend despite increase of wind and solar generation, due to system operators collaboration. PCR Primary, SCR Secondary and TCR Tertiary control, p for positive and n for negative. Costs for activated energy (above) and reserved capacity (below).

6.2.3 Wind power participating in balancing task

A study of the real-time active power balance in a Danish power system with wind covering more than 50% of the consumption in 2020, using a 5-min balancing model and including wind power into the Automatic Generation Control (AGC) is presented in (Basit et al., 2014). The results indicate that wind power can provide effective and cost-efficient down-regulation, reducing the power imbalances in real-time operation and due to its fast ramp rates can provide quick Area control error (ACE) compliance.

REserviceS project analysed the impact of utilizing wind power and PV in frequency reserves. There were clear benefits at higher shares of variable generation (Figure 34). Not all wind and PV units need to participate, in the simulations the benefits as well as an adequate frequency response were achieved with one quarter of the units capable of frequency support. The frequency response with wind ad PV power plants can be as good as with other type of power plants or even better, assuming suitable control structures and settings. However, high amounts of rapid response with a delay in sensing the frequency changes can lead to system stability issues and needs to be mitigated in the control system used for frequency control (Kiviluoma et al., 2014).

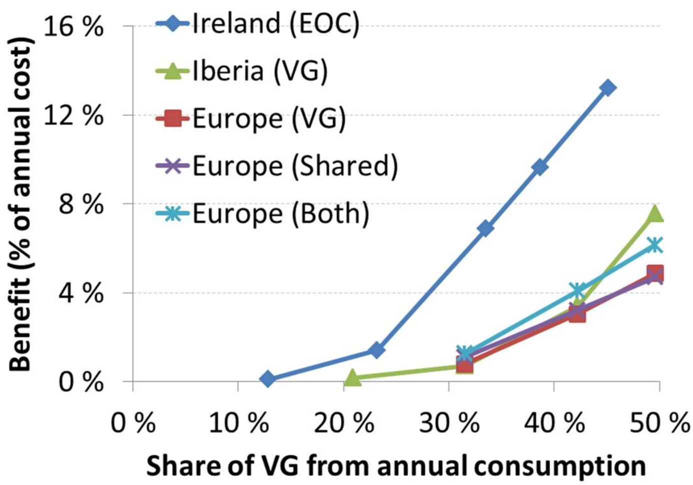


Figure 34. System benefits (decrease of annual operating costs) when introducing wind power and PV in frequency reserves will increase at higher shares of variable renewables (source: ReServiceS D5.5, see Kiviluoma et al., 2014).

6.2.4 Experience of imbalance costs for wind power from the markets

Wind power generators are already bearing the extra balancing cost incurred into system operation in many markets, and in some markets even exceeding them. Based on a consultation among industry in Europe, balancing cost for wind power generators are 2–3 €/MWh on average (EWEA, 2015). There were some notable exceptions: in the upper side Bulgaria imposes imbalances charges in the range of 10 to 24 €/MWh and Romania between 8 and 10 €/MWh when the wind power generators are not part of an aggregator. In the lower side, Spain imposes imbalance charges of 1 €/MWh (Figure 35). In 14 out of 18 members states surveyed wind power generators are already balancing responsible in some form.

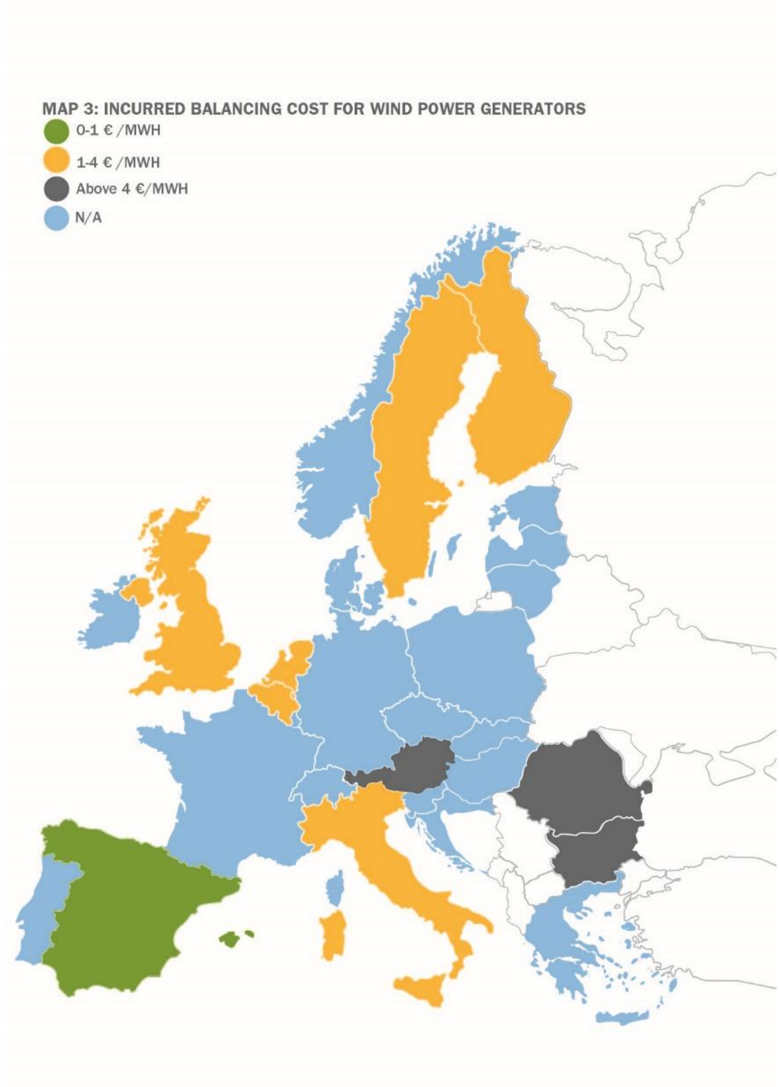


Figure 35. Balancing costs from forecast errors for wind power producers in the electricity markets (source: EWEA, 2015).

The balancing costs for wind power production in the Nordic countries is overall in a moderate level, 1–3 €/MWh cost for the whole generation, as reported in previous Task 25 summary reports (Holttinen et al., 2012). For Finland, 3 years of data was analysed giving a balancing cost of 2–3 €/MWh for one site, reducing to 1–1.4 €/MWh to aggregate 24 sites. Aggregation of sites lowers relative share of balancing costs considerably, up to 60%. The costs are strongly dependent on balancing market (Nordic Regulating Market) prices that determine the prices for the imbalances. Similar level of forecast errors resulted in 40% higher imbalance costs for 2012 compared with 2011 (Holttinen et al., 2013).

In Denmark wind power is already impacting the market prices a lot and causing very low, even negative prices during surplus generation in the power system. Most wind turbines are paid a production subsidy, a fixed amount in excess of the spot price (onshore) and a fixed amount per MWh produced (offshore), no matter the market prices. This makes them bid to market even negative prices (a price of minus the subsidy amount). To mitigate the surplus generation situations, the new offshore wind power plants, like Anholt (400 MW) is paid a fixed amount per MWh produced but no refund if spot price is negative. Instead the owner must pay the negative spot price for producing. Many offshore wind power plants and some onshore turbines bid into the regulating power market (down regulation). The bidding price is normally equal to minus the production subsidy they would get.

6.2.5 Cycling impacts and emissions reductions due to wind power

In the USA, the Western Wind and Solar Integration Study was extended in a second phase to include a 5-minute economic dispatch model, examining in detail the impact of cycling of thermal units on integration (Lew et al., 2013a). The WWSIS2 study developed detailed information concerning the cost of power plant cycling and part-load operation. Parameters that describe these costs were input to the production simulation tool so that the increase in cycling that was caused by wind and solar energy could be calculated in a robust manner, and based on best-available information and simulations.

The study found that electricity production costs declined by \$29.40–\$30.60 per MWh of wind and solar generation, depending on the specific mix of wind and solar generation. Cycling of thermal plants – primarily gas plants – reduce this by \$0.14–\$0.16 per MWh of wind and solar. This is shown in Figure 36.

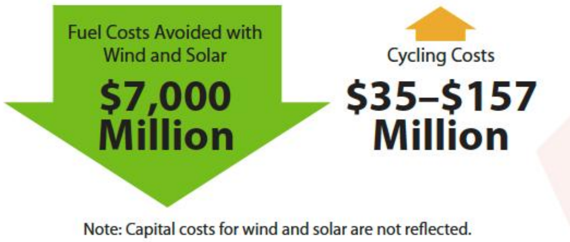


Figure 36. From a system perspective cycling costs are relatively small. (Source WWSIS2, see Lew et al., 2013.)

These costs are highly dependent on the specific generation characteristics of the modeled fleet, but they indicate that cycling costs are a relatively small percentage of the reduction in operating cost that can be achieved with wind/solar energy.

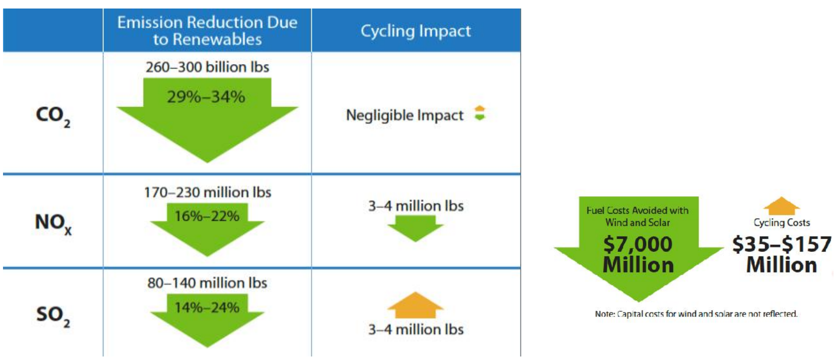


Figure 37. Impact of increased cycling of thermal power plants on emissions and costs of balancing. From a system perspective, cycling costs and emissions impacts of cycling are relatively small. (Source WWSIS2, see Lew et al., 2013a.)

In Minnesota, operational starts of the coal units due to economic commitment from the production simulation results are shown in Figure 38. This figure enables a direct comparison of how increased wind and solar penetration affects the cycling duty if the coal units are economically committed by the energy market. Cycling duty increases significantly on nearly all coal units (MRITS, 2014). Most coal plants were originally designed for baseload operation. Increased cycling duty could increase wear and tear on these units, with corresponding increases in maintenance requirements. Many coal plants in MISO presently are designated by the plant's owner to operate as "must-run" in order to avoid start/stop cycles that would occur if they were economically committed by the market. Scenarios S1a and S2a assumed that all coal plants in MISO are subject to economic commitment/dispatch (i.e., not must-run) based on day-ahead forecasts of load, wind and solar energy within MISO. Production simulation results show significant coal plant cycling due to economic market signals:

- Small coal units (below 300 MW rating) could have an additional 100 to 200 starts per year, beyond those due to forced or planned outages.
- Large coal units (above 300 MW) could have an additional 20 to 100 starts per year

The start/stop cycles of coal plants would sometimes have down-times of less than 2 days. If the unit commitment process was modified to use a longer term forward market (say 3 to 5 days ahead), then coal plant owners could adjust their operational strategy to consider de-committing units when prolonged periods of high wind/solar generation and low system loads are forecasted. A forward market would depend on longer term forecasts of wind, solar and load energy, consistent with the look-ahead period of the market. Although such forecasts would be somewhat less accurate than day-ahead forecasts, the quality of the forecasts would likely be adequate to support such unit commitment decisions.

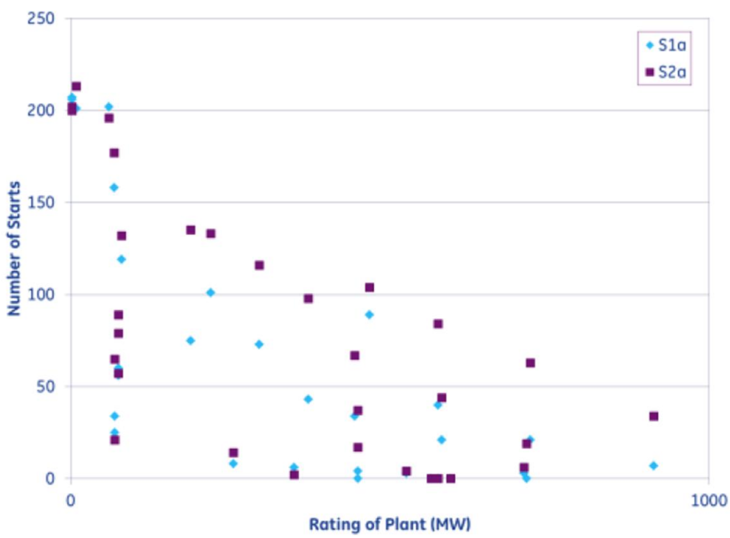


Figure 38. Annual operational starts of coal units in Minnesota due to economic commitment. Scenario 1a has 40% and Scenario 2a 50% wind and solar energy. (Source: MRITS, 2014.)

Scenarios S1 and S2 of the Minnesota study assumed almost all coal plants would continue to operate as they do today. Coal units were on-line all year (except for scheduled maintenance periods) and were not de-committed during periods of low market prices. The results of these scenarios confirmed that the coal units could remain must-run with minor impacts on overall operation of the Minnesota-Centric region. Coal plant owners could choose to continue the must-run practice to avoid the detrimental impacts of increased cycling as wind and solar penetration increases. Doing so would likely incur some additional operational costs when energy prices fall below a plant's breakeven point. Wind curtailment would also be about 0.5% higher than if the coal plants were economically committed.

Ways of estimating CO_2 reductions of wind power using different methodologies are presented in (Holttinen et al., 2015). Estimates based on historical data have more pitfalls in methodology than estimates based on dispatch simulations. Taking into account exchange of electricity with neighbouring regions is challenging for all methods. Results for CO_2 emission reductions are shown from several countries. Wind power will reduce emissions for about 0.3–0.4 $MtCO_2$/MWh when replacing mainly gas and up to 0.7 $MtCO_2$/MWh when replacing mainly coal powered generation (Figure 39).

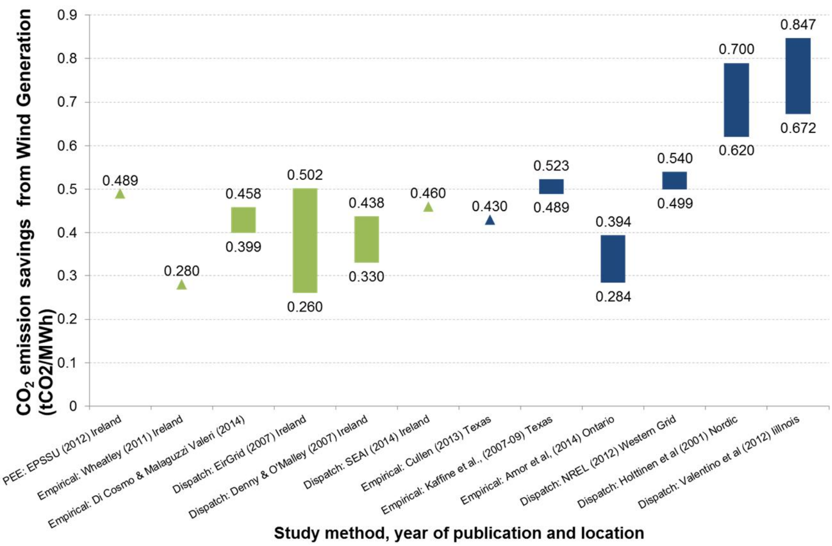


Figure 39. Comparison of emission reductions from wind power. Power systems where predominantly gas is replaced in green, compared to estimates for power systems where predominantly coal is replaced (blue). (Source: Holttinen et al., 2015.)

6.3 Operational practices

There is already experience in managing large shares of wind power in the power systems. Balancing larger areas than single balancing areas is one key to wind integration – the evolving markets with cross border sharing of balancing resources is one example presented more in detail in Section 6.3.2.

6.3.1 Experience in managing wind power in power system operations

Experience on coping with high instant wind power shares in the system has been reported in (Ackermann et al., 2015; Söder et al., 2012; Holttinen et al., 2011; Söder et al., 2007). **Using updated forecasts and on-line information of wind power generation in system operators' control rooms** is one key to wind integration, used today in power systems with considerable shares of wind power.

Denmark is managing the >100% shares occurring approximately 75 hours per year by **exporting to neighbouring countries** Norway and Sweden. In Portugal, more than 100% share of wind power was reached in 2015 for the first time, and the situation was handled with exports and increased pumping in pumped hydro stations (Figure 40).

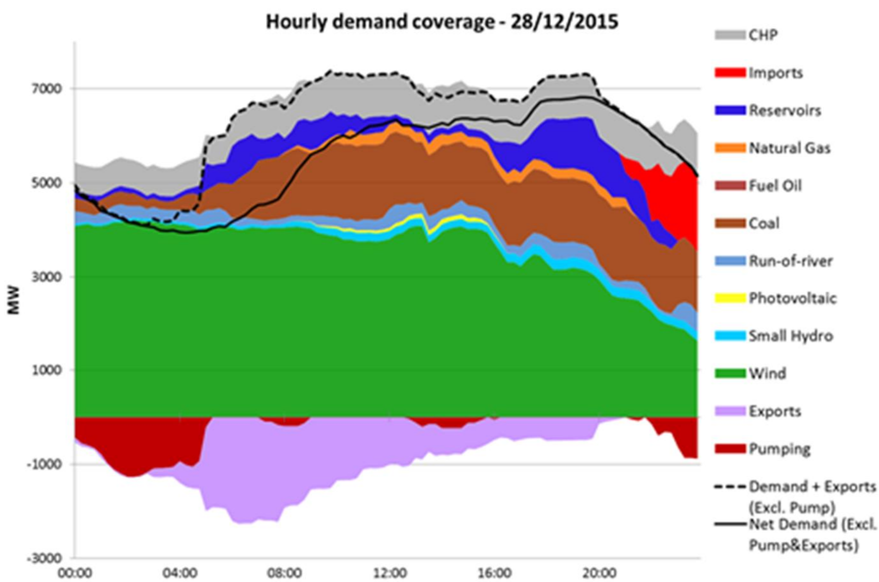


Figure 40. Incident where wind power production exceeded electricity consumption in Portugal, for a couple of hours during the night.

In Spain, the TSO uses the **possibility to curtail wind power in critical situations**, through the capabilities of Control Centre for Renewable Energies (Ackermann et al., 2015). In Ireland, due to frequency and dynamic stability concerns, the system operator EirGrid **limits the instantaneous penetration of asynchronous generation** (wind power and HVDC imports). Eirgrid has become comfortable enough of managing the 50% instant shares of wind power that the limit has been increased to 55% of demand plus exports. It is envisaged that this limit will rise in stages to a maximum of 75% in 2020 when a number of remedial measures are implemented. These include new ancillary services products and new grid code requirements including an increased requirement for all generation to remain synchronised during rates of change of frequency up to 1Hz/s. Since November 2014, EirGrid also enforce an operational constraint to ensure a minimum of 20,000 MWs of inertia on the system.

Issues related to increasing unscheduled flows on the electricity system are often related to wind and solar PV power generation. **Loop/transit flows in Central Europe** and market impact of measures that may be applied to address these challenges have been studied in (Thema consulting, 2013). One main factor as the root cause for loop flows is insufficient price signals. The market prices do not correctly reflect the physical grid, and do not account fully for internal congestions within bidding zones. Second root cause is the increase in energy imbalances as the ever increasing shares of variable RES imply a reconfiguration of supply and loads in the energy system, and hence the transmission grid. Mitigation measures proposed are bidding zone delimitation in order to improve price signals, the implementation of Flow-based market coupling (FBMC) to accompany bidding zone delimitation and lastly more coordinated grid developments as a long term measure. Furthermore, bilateral or regional mechanisms for cooperation and compensation could be a tool for addressing the distribution of costs and benefits related to loop and transit flows which are not directly addressed by flow- based market coupling should be considered by policy makers.

The first experience is emerging for **wind power providing system services**, so called ancillary services. Wind power plants can actively participate in over-frequency situation by down-regulating generation. In under-frequency events, their capability might be limited if not operating down-regulated. By utilizing wind power in frequency response more thermal and hydro power plants can be shut down and their fuel/water use can be reduced. In Italy the provision of downward tertiary reserve and the downward balancing services have been studied to be possible with low costs in the necessary communications and control systems for units connected to the high voltage grid. Technical capabilities for automatic frequency control have been tested in Denmark (in Horns Rev offshore wind power plant) and in the EU project Twenties demonstrations for frequency and voltage support at transmission level (in Spain).

In Denmark manually activated frequency support service are sometimes used at the balancing market (Nordic Regulating Power Market). Wind power plants bid down-regulation to the regulating power market and sometimes the bids are used. A bid of 20 MW activated in the regulating power market will result in an hourly schedule of 100 MW to be treated as 80 MW in balance settlement.

Example of wind power providing automatic frequency control is available from the USA Xcel/Public Service of Colorado (PSCO) balancing area. In 2014, PSCO had 19% wind and 1% solar energy penetration on its fairly small (7 GW peak) system. Wind served more than 50% of the load during 6% of the hours in October 2014, and it reached a peak of 60% on 24 May 2013, between 1 and 2 a.m. When loads are low at night and wind is high, PSCO has to decide between deeply cycling their coal-powered plants or curtailing wind power output. Wind curtailment provides two benefits: reduced coal cycling can avoid potential high-impact, low-probability events and curtailed wind can provide an upward regulating reserve. Wind can be curtailed manually through a block curtailment, which is a reduction in wind power plant output by a fixed amount for a period of time. Example of wind curtailment of 200 MW in a windy night is seen in Figure 41, when putting the wind power plant on AGC regulation. Adjusting output up and down as appropriate was used to help keep the area imbalance (Area Control Error ACE) within specified limits up until 6 a.m.

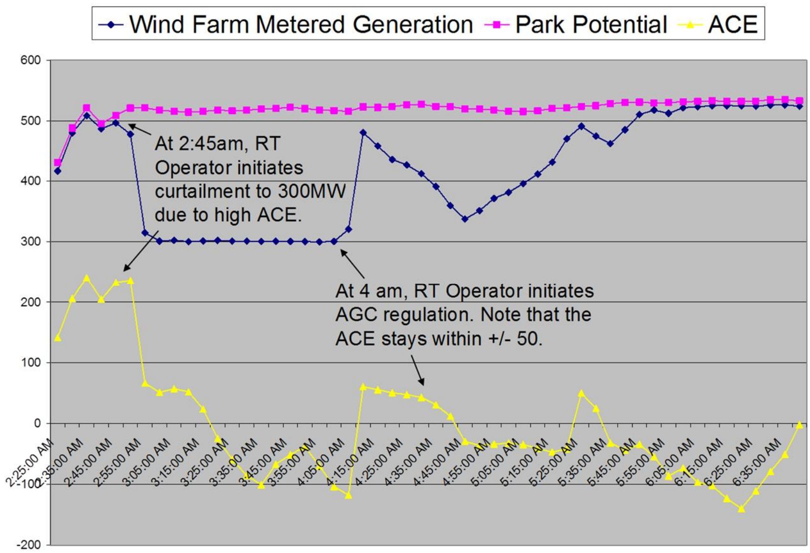


Figure 41. Operational experience of a Colorado wind power plant providing fast frequency response (AGC automatic generation control) to help system Area Control Error (ACE) remain close to zero.

The field tests in Germany have shown that although renewable energy sources are already technically in a position to provide control reserve the framework conditions of the balancing market currently prevent renewable energy sources from actually offering these abilities. With shorter tender announcement periods and lead times, photovoltaic systems and wind turbines, whose feed capacities can only be predicted precisely with a lead time of a few hours up to roughly one day, can participate in the balancing market. Also, the verification of the control reserve provision should be based on the actual “available active power” of wind turbines and photovoltaic systems. If fluctuating generators had to provide control reserve like existing providers, they would have to conform to a constant chronological roadmap. On one hand, this would have the disadvantage that the fluctuating generators would have to be scaled down to a constant level, leaving much potential energy unused. On the other, it would mean that the compensating effects between the generators and loads could not be used. (Fraunhofer IWES et al., 2014.)

6.3.2 Integrating wind power to electricity markets

Integrating wind power to electricity markets is one operational practice with positive experience. **In Europe**, integration of Balancing Markets and the exchanging and sharing of reserves could achieve operational cost savings in the order of € 3bn/year and reduced (up to 40% less) requirements for reserve capacity. Furthermore these annual trading benefits are at least one order of magnitude higher that the "one-off" cost of implementation in IT and related systems. (MottMacDonald & Sweco, 2013.)

In Texas, US, wind generation is incorporated into a 5 minute dispatch with a persistence forecast. This helps the system operator ERCOT to manage the variability with the flexibility inherent in the dispatch stack with the 5 minute dispatch. The uncertainty due to forecast error with is managed with regulation within the 5 minute dispatch period, and the occasional use of slower 30 minute reserves. ERCOT also implemented a nodal market in December of 2010, featuring locational marginal pricing (LMP) for generation at more than 8,000 nodes, a day-ahead energy and ancillary services co-optimized market, day-ahead and hourly reliability-unit commitment, and congestion revenue rights. Since that time, it has been able to integrate increasing amounts of wind capacity with much less difficulty than under the previous zonal market design, with installed wind capacity in excess of 12,000 MW at the end of 2014.

Potential impact of an Energy Imbalance Market (EIM) **in the Western US** is an example of changes to regional market designs to accommodate higher penetrations of variable output renewable resources (https://www.caiso.com/informed/Pages/EIMOverview/Default.aspx). Milligan et al. (2014) undertook a detailed sub-hourly analysis of several scenarios of the EIM that consisted of alternative membership in the market ranging from nearly the full interconnection to 3 distinct EIMs organized around the existing transmission planning organizations. Figure 42 shows "heat maps" of the US portion of the interconnection, with (right) and without (left) the EIM. As would be expected, the creation of a larger market introduces an increase in efficiency because, at least some of the time, there will be less expensive assets outside of a given balancing region that can only be accessed thru the EIM. Subsequent to this study, the CAISO and PacifiCorp announced the creation of an EIM, operated by the CAISO and scalable to many participants, based on interest and participation. In 2015 NV Energy joined. In 2016, Puget Sound Energy and Arizona Public Service are scheduled to join, followed by Portland General Electric in 2017 and Idaho Power in 2018.

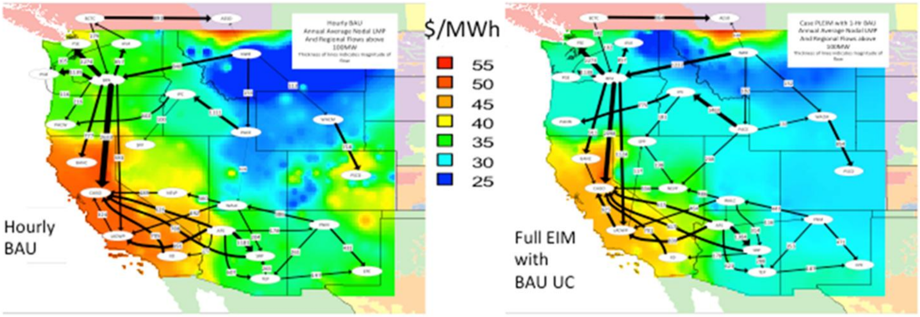


Figure 42. Results from the EIM analysis show that combining balancing resource of the balancing areas, the cost of balancing will be reduced for most of the areas – only the areas having very low balancing costs (dark blue) will see a slight increase when sharing their resources. (Source: Milligan et al., 2014.)

In Ireland detailed design rules are currently being developed for the new EU Target Model compliant electricity market known as I-SEM. The resultant market structure is more suited to operation with large amounts of renewable energy (EirGrid, 2015b). Some key features of the new market structure which will impact on wind power are:

- A day-ahead and continuous intra-day balancing market which allows economic dispatch of plant to manage imbalances of variable renewables (mainly wind).
- Ancillary services markets: EirGrid, under the DS3 Programme (Delivering a Secure, Sustainable Electricity System) is in the process of consulting on a new range of ancillary services products related to frequency control such as payments for providing a ramping service and fast frequency response. It is envisaged that some types of wind generation could contribute to the latter service through provision of a synthetic inertial response (EirGrid, 2015b).
- No compensation for system level variable renewable curtailment (unless related to transmission congestion) from 2018.

Many different approaches for market design can enhance successful wind integration. There is a great deal to be learned by examining the differences in approaches, understanding what works well and what doesn't, and continually searching for new and improved approaches with ever higher penetration of renewable energy (Smith et al., 2014). A comparison among the current state of resource adequacy, operational flexibility, and transmission capability in the context of the integration of renewable energy in power systems showed that there are many areas of commonality between the US and Europe, but there are also some differences (Smith et al., 2014):

1. The integration of low marginal cost renewable energy is driving numerous approaches to providing capacity adequacy in the US and Europe, includ-

ing energy-only markets, capacity markets, and hybrid approaches involving a regulatory capacity planning reserve margin requirement. The US and Europe are similar in this regard, although the need to address this problem is more urgent in Europe.

2. Operational flexibility comes from several sources. One is in the optimization of dispatch over a larger area, as the EU is trying to do with the integrated market concept and as is happening in the US with physical and virtual consolidation of balancing areas. Greater geographic and resource diversity can help manage renewables in real-time operation. Another is the use of ramping capability in the dispatch process (and even including wind in the 5-minute dispatch as is done by several ISOs/RTOs in the US) with the use of reserves to manage more extreme events while co-optimizing energy and reserves. Additional measures are also in evidence, such as more stringent grid codes for improved performance and demand side participation.
3. Policies for transmission build out and cost allocation are explicitly needed for renewable integration. The EU has a system in place for doing this, and the US is moving in this direction.

Market involvement of a producer considering uncertainty in the wind power and electricity prices can be helped with two-stage adaptive robust optimization. Bidding in different markets (e.g. pool, forward and intraday markets) will maximize the bidders' profit (Lopes et al., 2013b; Lopes & Algarvio, 2014). Relations between the uncertainty of the wind power and the level of the contracts signed to hedge against the volatility of the prices in the pool can be captured (Lima et al., 2015).

6.4 Demand side flexibility

An article with IEA Task25 participation reviewed literature on how demand side flexibility has been used to mitigate wind power and PV variability (Nolan et al., 2014). It identified four key areas for the creation of benefits: energy arbitrage, provision of ancillary services, contribution to generation adequacy and deferral of investments in networks, and overall system cost reduction. A number of barriers were also identified, that currently prevent full participation of demand response in the power markets and ancillary services.

In Japan a demonstration project to control power consumption of three heat pump water heaters used by local consumers in Aomori (northern Tohoku) was implemented. It was shown that the total power consumption of the heat pump water heaters increases and decreases according to up and down of power system frequency. However, the heat pump water heaters had several ten seconds delay in changing power consumption after on/off signals (Kondoh, 2013a), although their control boards measured frequency every one second and sent the control signals just after it exceeded thresholds (Kohdoh, 2013b).

In UK the analysis presented in (Aunedi et al., 2014) demonstrates that smart demand side technologies (including electric vehicles, heat pumps, industrial and commercial demand side response and dynamic time of use) are capable of supporting cost-efficient integration of wind in Great Britain 2030 and 2050 systems.

In Germany DSM is seen as a promising flexibility option for the integration of wind and solar Power. In an Agora study (Agora, 2013) the potential in industry for DSM in the Southern part of Germany is calculated to be at least 850 MW for duration of 1–2 hours. The costs of DSM measures in Germany were evaluated in (Gruber, 2014). About 3,500 MW are available with low marginal costs (< 20 €/MWh). The potential for load shedding with electricity-intensive processes is about 4,800 MW, but with rather high marginal costs from 100 to 500 €/MWh.

6.5 Energy storage

Storage options are studied in wind integration studies as a system-level tool for balancing load and generation. A Task 25 summary was published in (Estanqueiro et al., 2012).

6.5.1 Electricity storage

In Italy, In 2011 the Italian TSO (Terna) promoted the implementation of special pilot projects for RES integration and for testing capabilities and constraints about the possible delivery of ancillary services by electrochemical energy storage power plants. The main aim of the pilot projects, duly authorized by National Regulator Authority, was the design, construction and operation of a set of energy storage power plants, with different technologies, to verify the effective benefits which could be addressed to the Italian power system by a large integration of this technology. In 2014 the pilot projects have been implemented into 5 different power plants, located in several sites: 3 of them, in the South of Italy, were dedicated to “energy intensive” projects (35 MW), characterized by an energy/power ratio of about 8 hours using NaS technology batteries, another one was located in Sardinia island (8 MW), the last one in Sicily island (8 MW). The last two projects are defined “power intensive” because they are characterized by an energy/power ratio between 0.5 and 4 hours using SoNick and Li-ion technology batteries. The “Energy intensive” project allows to recover hundreds of GWh produced by wind power plants, energy that is currently not used. This includes greater savings for the entire country as well as benefits for the environment through the substantial reduction of CO_2 emissions. One of the most important outcome of “power intensive” projects is the demonstration of high-level performances in terms of very fast active power response, which are useful especially for Frequency Containment Reserve (FCR), synthetic inertia and integration into Special Protection Schemes of system defence plans.

In Portugal the impact of electric vehicles (eVs) to static and operational reserve was assessed. Both uncontrollable and smart charging strategies increase the load demand, but in different hours. 11% share of eVs increased the EENS (energy not served) index somewhat but sufficient static reserve was available. Impacts to operating reserve were more significant: the possibility to increase the secondary reserve using EV would be beneficial when compared with the scenario without EV (Madureira, 2012).

Pumped hydro and electric vehicles storage systems were assessed for their possibilities in assisting the TSO during excess of wind and run-of-river generation (Mateus, 2011; Mateus & Estanqueiro, 2012). The regulation based on the distributed storage of EVs may have a relevant contribution for the absorption of the excessive energy delivered by the non-dispatchable fleet, however, EVs are not fundamental, since the maximum power surplus in the three scenarios studied for year 2020 will not exceed the pumped hydro capacity planned for 2020.

In Ireland recent work regarding the value of storage (O'Dwyer and Flynn, 2013) has investigated various combinations of installed storage capacity, storage volume, interconnection levels and installed wind capacity Figure 43. The main conclusions are:

- Generation capacity in MW has a much higher impact on the value of storage than the storage volume in MWh.
- In all scenarios examined, annual operational costs savings from storage exceeded annualised capital costs up to 300MW installed capacity.
- Increased levels of interconnection produce a similar benefit to storage and thus reduce its value.
- Wind curtailment reductions (up to 385 GWh for the base wind scenario in 2020) increase almost linearly with storage plant size.
- Cost savings are driven by the storage plant's flexibility, with storage plant used extensively to supply reserves and allow the system to operate more efficiently with reduced start-up costs and more efficient loading of the conventional plant.

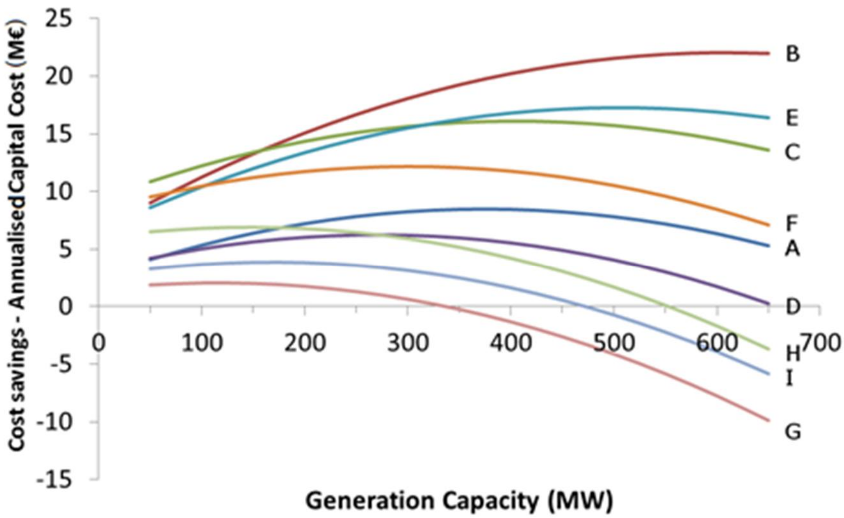


Figure 43. Benefits of pumped hydro storage in Ireland with increasing pumped hydro capacity in year 2025. The scenarios A…I are with different options of storage size (2 and 10 hours), installed wind and limit for instant wind penetration (50 or 75%). Most cost effective are the ones with only 2 hour storage (with high wind B, and medium wind E).

In the USA, Denholm et al. (2013) estimated the value of storage in a test power system based on the state of Colorado, using combination of the Public System of Colorado and Western Area Colorado Missouri (WACM) balancing areas. The study uses an energy penetration level of 11% from wind and solar. Modeling was done with the PLEXOS production simulation model, and several storage scenarios were considered. In each case, the value of storage was calculated as the reduction in system operating cost made possible by the storage scenario in question. The value of storage was calculated for providing energy services and for providing regulating reserve and spinning/contingency reserve. These functions were modeled separately so that the individual contributions of storage could be measured independently. In addition, a combination case for storage provision of both energy and reserve was analyzed. A 300 MW storage unit was used with no ramp constraints, a 75% round-trip efficiency, and 8 hours of capacity at full output. For the reserves-only modeling, the device is also not ramp-constrained and uses a 100 MW device. Because the storage devices are not 100% efficient, they consume energy, even in regulation mode. The size of the storage device was altered as a parameter to investigate how its value changes as a function of penetration. The results for the energy-only simulations are shown in Figure 44.

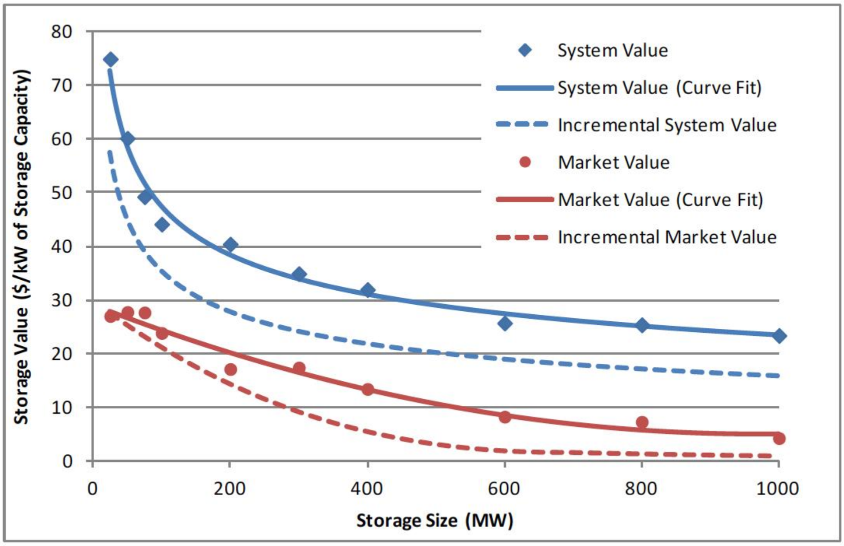


Figure 44. Value of storage as system value (reduction in production cost) and market value – the revenue that a storage device could expect to receive in the market. Incremental curves show the impact of additional (incremental) storage, whereas the value curves show total value for the given level of storage.

Taken as a whole, the results show that there is value from storage as an energy source; however this value is relatively low. This is because storage competes with alternative services, such as conventional units' dispatch.

6.5.2 Hydro power storage

Hydro power is one of the most flexible sources of electricity production. Power systems with considerable amounts of flexible hydro power potentially offer easier integration of variable generation, e.g. wind and solar. However, there exist operational constraints to ensure mid/long term security of supply while keeping river flows and reservoirs levels within permitted limits. In order to properly assess the effective available hydro power flexibility and its value for storage, detailed assessment of hydro power is essential. Due to the inherent uncertainty of the weather dependent hydrological cycle, regulation constraints on the hydro system, and uncertainty of internal load as well as variable generation (wind and solar), this assessment is complex. Hence, it requires proper modelling of all the underlying interactions between hydro power and the power system with large share of other variable renewables (Huertas Hernando et al., 2016).

Hydro power already has an important role for wind power integration in Denmark (through Nordic market) and in Spain and Portugal. In the USA the importance of hydro generation in the Pacific Northwest has been recognized, however, reservoirs in the area must serve multiple purposes, which often prevail over electricity production and complicate assessing the benefits of hydro power flexibility (Huertas Hernando et al., 2016). The simulated operation of hydro power plants in a more detailed model (Riverware) was compared to the typical simplified assumptions that are included in power system modelling with PLEXOS model (Ibanez et al., 2014). There was a significant benefit to the power system because of the increased flexibility in the hydro system as represented by RiverWare:

- Under a business-as-usual scenario (BAU), total productions costs were reduced by 2%.
- A high-wind scenario saw a reduction of 16% in the amount of VG curtailed and a 0.6% decrease in total production costs.
- In both BAU and high-wind cases, extreme marginal price spikes were reduced

In Norway, water reservoir management and hydro production was compared in low to high wind share scenarios in 2010 and 2030, respectively (Farahmand et al., 2015). Based on stochastic dynamic problem taking into account the long-term scheduling of hydro power, the strategic utilisation of hydro power stored in reservoirs was estimated. The diagrams show the percentiles of values based on 75 climatic years. In 2010, the reservoir handling was quite characteristic of the Nordic countries, with a depletion during the winter and early spring, and a filling during the other time of the year. Assessment of the reservoir handling for the future scenarios in 2030 shows that the reservoir levels become higher in general, while the long-term reservoir storage capability is utilised less (Figure 45). This means that percentiles of the reservoir handling become more spread and flatter. It also indicates a change of the reservoir utilisation from a long-term perspective to a more short-term perspective.

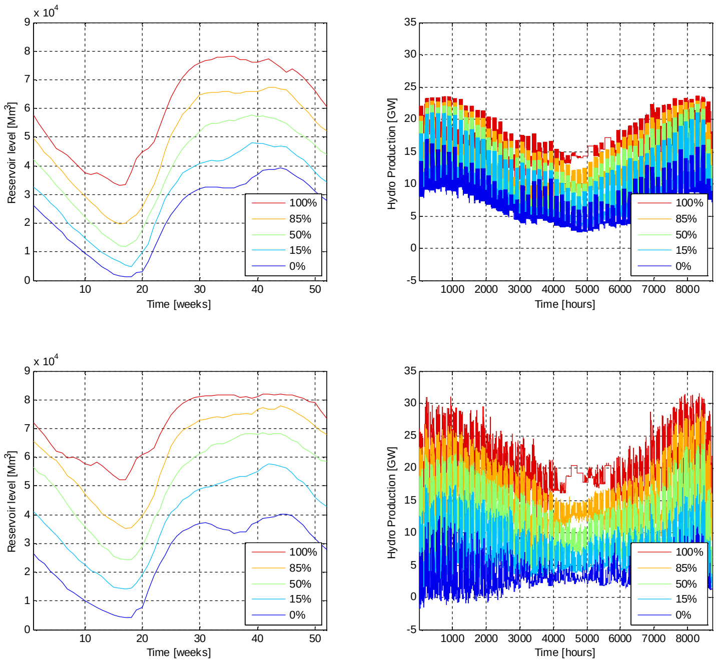


Figure 45. Hydro power reservoir levels (left) and hydro power generation (right) for year 2010 and year 2030 with wind power. The graph shows percentiles from 75 years (50% average, 100% wet and 0% dry years).

A correlation between the pumping strategies in the Norwegian system and the onshore and offshore wind variations around the North Sea was observed in TWENTIES project (Farahmand et al., 2013). The flows across a meshed offshore grid are also strongly influenced by onshore grid constraints in Continental Europe and UK. This will affect the optimal use of wind and hydro power. The amount of pumping hydro power plants increases with the amount of constraints in the grid. This reflects the increased need for flexibility in continental Europe due to congestion and wind power.

The modelling challenges regarding hydro power are discussed in (Huertas Hernando et al., 2016).

6.5.3 Heat and gas storage

Possibilities to utilize flexibility from heat generation and use was studied for a **Finland** size future power system (Kiviluoma, 2013). Heat measures were notably better than smart charging electric vehicles in providing flexibility for the integration of wind power. The analysis was performed with a stochastic unit commitment model (WILMAR) and a generation planning model (Balmorel). Electric boilers can absorb excess power generation and enable shutdown of combined heat and power (CHP) units during periods of high wind generation and low electricity demand. Heat storages can advance or postpone heat generation and hence affect the operation of electric boilers and CHP units. The availability of heat measures increased the cost optimal share of wind power from 35% to 47% in one of the analysed scenarios.

In China, curtailment levels in excess of 20% have been experienced, primarily due to a high capacity of inflexible CHP plant. The potential for use of heat storages and electric boilers to deliver flexibility in the Northern China power grid was studied by Tsinghua University in collaboration with University College Dublin (Chen et al., 2015). In the test system studied, results showed that use of electric boilers reduced local curtailment from 34.9% to 5.6% and use of boilers was more effective at reducing wind power curtailment than use of heat storage. However, use of heat storage provided the most economic benefit. Use of both technologies together showed greatest long term benefit.

Denmark's high targets for wind power calls for energy system integration between electricity, gas and heat sectors, as described in Chapter 7.

7. Pushing the limits: Integration studies for >40% shares of renewables

Summaries of recent wind integration studies, studying more than 40% share of wind in yearly electricity consumption are presented here.

7.1 Denmark

Denmark is aiming at a 30% renewable energy share of its total energy consumption by 2020, which is estimated to result in a 50% electricity demand coverage by wind energy in 2020. Danish political energy targets state additionally not to use any fossil fuels by the year 2050. The 2014 wind share of electricity was at 40% and this is already challenging the Danish system e.g. concerning the need for flexibility on the one hand, or by pushing power plants delivering important system services out of the market on the other hand.

A broader way of system analysis and also new market design arrangements are supposed to be needed, incentivising the provision of more flexibility and also grid services needed by the system (e.g. inertia, short circuit power, black start capability, voltage control, dynamic voltage support and damping of system oscillations). Current large wind power plants are able to provide part of these needs, but additionally other options should be part of the Danish system, as e.g. static synchronous compensators or VSC HVDC connections to other systems.

In an initial broad study (Energinet.dk, 2015) the whole value chain from various energy resources down to energy services has been analysed, referring to many transition processes inside the energy system (Figure 46).

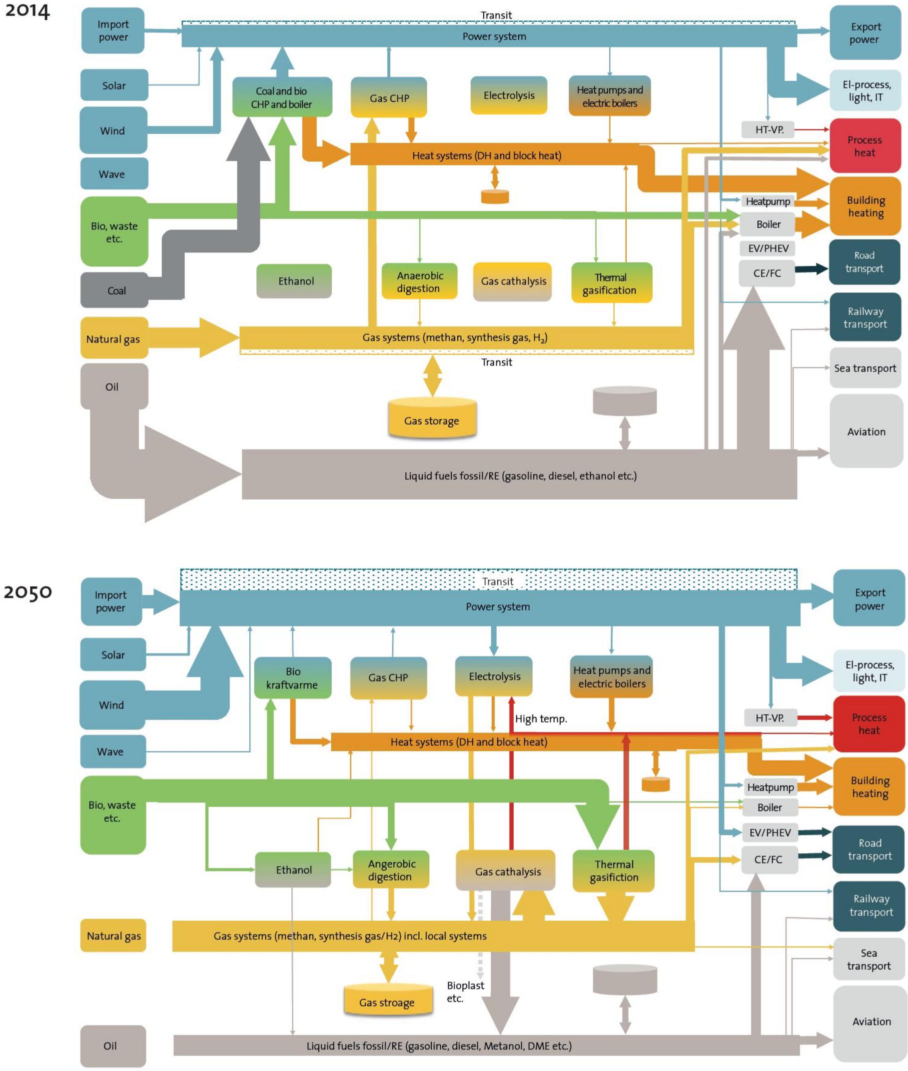


Figure 46. Energy flows in Denmark in 2014 and 2050, with indicatively scaled arrows (source: energinet.dk, 2015).

The analyses concluded that the energy use for all sectors (heat, transport, industry) will change significantly, e.g. the use of natural gas is expected to decrease to about a third of the 2011 level (Figure 47).

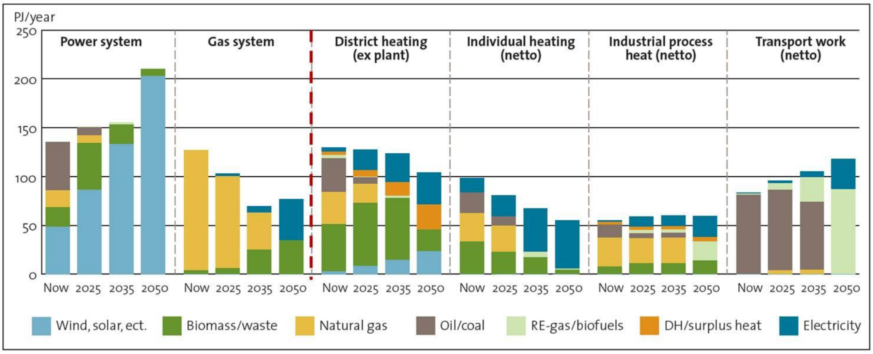


Figure 47. Possible Danish transition process: Left: production development. Right: future consumption development for different sectors

Flexibility needs for a “wind”-variant of the future have been evaluated by analysing the residual load (i.e. load minus wind minus solar power) for different time periods using 10 years of time series for Denmark and the neighbouring countries’ production and demand. Results showed that flexible demand and vehicle-to-grid provide very useful service in periods shorter than 5 hours, but that for periods lasting longer than 12 hours other means, like e.g. exchange with neighbours gets more important, as they might have spare capacity when Denmark needs support.

Especially for periods between 12 hours and one week, the availability of flexibility has to be ensured using market means. This means that flexibility should get a price reflecting the marked needs. Another option might be to change the accounting system for balancing power from partly being socialized in grid tariffs to consumers, to where the responsible market participant has to finance the imbalances. This might result in a movement of the imbalances from the hour of operation to intraday or even day-ahead markets. In spring 2014 a process has been launched by the Danish TSO Energinet.dk to review the current market arrangements and planned changes/developments concerning prerequisites and framework conditions with respect to – among others – flexibility needs, DSM options, all fuel types nationally/internationally and the planned market arrangements in surrounding countries as well. In depth discussions with neighbouring countries are ongoing, who also face similar challenges.

7.2 Germany

The German energy transition ‘Energiwende’, change in policy to move towards renewables is attracting increasingly many studies looking at up to 100% renewable system. The required renewable shares in electricity are estimated to 95% until 2050 in order to achieve the goal, to avoid the emission of non-CO_2-greenhouse gases (especially in the agriculture sector). Wind and solar are playing the largest part (Repenning, 2014).

The future near 100% renewable system is found feasible in theory, looking at hourly energy balances, assuming net import from neighbouring countries will increase. An enhancement of storage capacity is dominated by power-to-gas, electric vehicles and heat storages (Benndorf, 2013; Nitsch, 2014; Repenning, 2014).

The calculations within the German research project “Kombikraftwerk 2050 (Renewable Power Plant 2050)” show that with appropriate adjustments to the system, the current high supply quality need not be compromised to implement the German energy transition. However, the system requires large storage capacities to reach 100% in the electricity sector. They must also be suitable for providing ancillary services. Storage use, grid expansion, scope of re-dispatch measures and the use or capping of energy surpluses are mutually dependent on one another. An installed capacity of bioenergy and methane power plants at roughly the same level as the maximum load should be available. The thermal power plants are mainly planned for generation of synthetic methane and hence can be seen as long-term storage units (after fuel switch). Import/export was assumed conservatively leading to higher capacities of thermal power plants. And it is worth noting that the results of 100%-scenarios are really driven by the basic assumptions and that there is still high variance in the results. Currently researchers from Fraunhofer IWES expect only 50–60% thermal power plants due to capacity values of wind and PV in addition to other flexibilities. The decentralised systems have to be networked, to compensate for frequency and local voltage fluctuations system-wide and in coordination. The frequency control should be dimensioned dynamically based on the forecast feed-in situation. The activation time for primary control reserve should be differentiated based on the energy source to compensate the reduced rotating mass with the technically feasible faster reaction times of wind and PV systems. Voltage was maintained at all times in the simulation. For additional local reactive power demand, e.g. in urban areas, it may be necessary to use some supplementary compensation systems. To optimise the provision of reactive power, the renewable energy systems should be connected at the highest voltage levels possible. Inverter-controlled systems should be able to contribute to voltage maintenance even during times they are not producing electricity.

7.3 Sweden

In Sweden a system with close to 100% renewable energy (Figure 48) has been performed (Söder, 2014). This shows a possibility of moving to a 100% renewable power supply when existing nuclear power plants are dismantled (65 TWh/a, started in 1972–86).

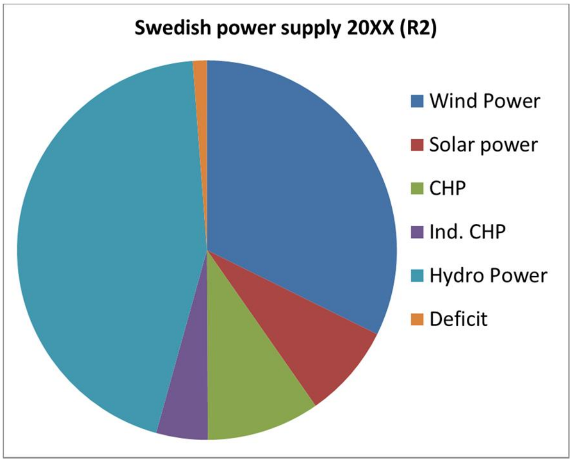


Figure 48. Energy supply in the studied future Swedish 100% renewable power system.

To reach 100% renewables a significant increase in wind- and solar power is assumed and the existing combined heat and power (CHP) would be 100% biofuelled which is realistic. In this study Sweden is seen as “isolated”, i.e. one cannot count on capacity supply from neighbors and the neighbors cannot take any possible surplus. This means a conservative approach since Sweden has a peak load of around 26 GW and a trading possibility with neighbors of around 10 GW. The main challenging parts are deficits, when there is high load and low wind. Here it was assumed that this was handled by installing gas turbines. They only supply around 1 percent of the energy but there is a need of around 5 GW of capacity. The cost for these is around 0.2 Eurocent/kWh when divided for all consumption. Import or flexible demand could be considered to mitigate this, if they have lower costs. Another challenge is the surplus, which occurs at high wind and solar during low load. The surplus is here assumed to be spilled which means that the cost of solar and wind power will increase with about 2–3%. Markets for the surplus including export and use of surplus in district heating of charging of electric vehicles could be considered to mitigate this. A general challenge in Sweden is that there are long rivers with many hydrologically coupled hydro power stations which cannot be used independently of each other. With much larger amounts of wind and solar power these stations will be used more frequently on maximum level (~800 hours/year) and minimum level (~800 hours/year). In addition to this there are uncertainties concerning wind power forecasts which have to be considered in the hydro power planning. These issues are currently studied further.

7.4 USA

The Midcontinent Independent System Operator (MISO) system was simulated with load flow, unit commitment and economic dispatch (UCED) and dynamic simulations, adding wind and solar generation to supply up to 40% of Minnesota's annual electricity needs (8 GW wind and 4.5 GW solar) and foreseen amounts of wind and solar in neighbouring MISO North/Central states (up to 38 GW wind and 6 GW solar). For a higher 50% wind and solar share in Minnesota and 25% renewable energy in MISO North/Central (10% above current renewable energy standards), UCED simulations were performed.

With significant transmission upgrades and expansions in the five state area (see Chapter 3) the power system can be successfully operated for all hours of the year: no unserved load, no reserve violations, and minimal curtailment of renewable energy (Figure 30). Dynamic analysis was not performed for 50% wind share so further analysis would be needed to ensure system reliability.

The production simulation results were analysed to assess system operational performance with respect to the following parameters; annual energy production by type of generating resource, renewable energy resource utilization and curtailment (Figure 32), cycling duty of thermal plants (Figure 38), adequacy of ramping capability of the MISO generation fleet, and risk of reserve violations and unserved load.

Adequacy of ramping capability of the MISO generation fleet is shown in Figure 49. The ramp rate capability of the conventional power plants are reducing as more wind and solar energy is added to the system.

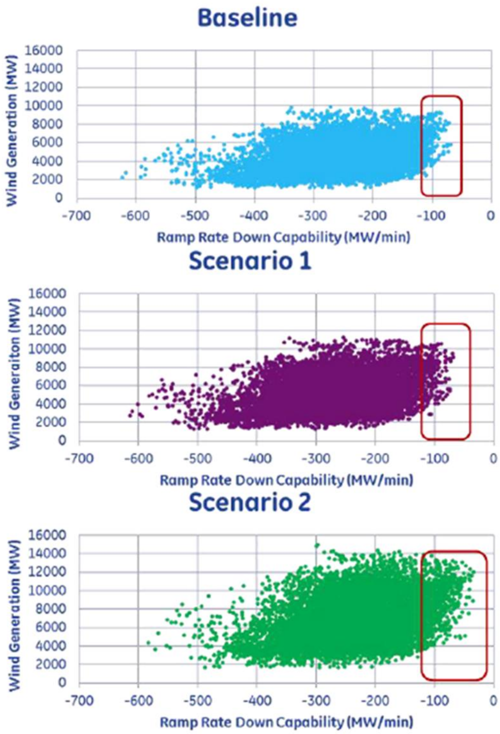


Figure 49. Scatter plot of ramp-rate down capability of MISO conventional generation fleet vs wind generation in Minnesota-centric region: Baseline 25%, Scenario 1 40% and Scenario 2 50% of wind and solar energy. (Source: MRITS, 2014)

In the USA, the Renewable Electricity Futures Study (REFS) (NREL, 2012) examined several scenarios of renewable energy, up to and including 90% of annual energy. Multiple scenarios were examined representing a wide range of differing assumptions regarding alternative transmission build-outs, level of flexibility in the non-renewable generation fleet, technology improvement, and renewable penetrations ranging from 30–90%. The mix of renewables included alternative levels of wind energy, solar energy, biomass, geothermal, and new hydro generation.

Figure 50 shows the generation mix from some of the alternative scenarios from the REF study. Even with the high level of variable renewable energy, the power system was balanced every hour of the year.

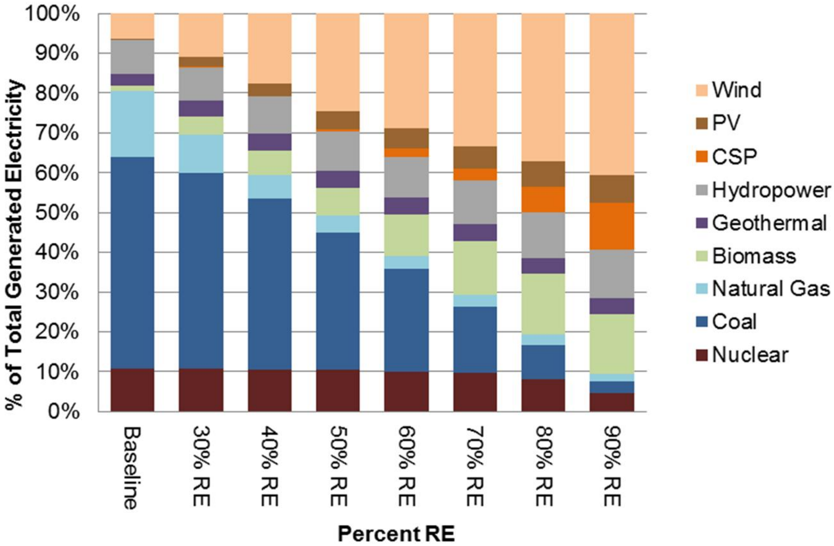


Figure 50. Energy mix from US Renewable Electricity Futures (source: Mai et al., 2012 – REF Executive Summary, page 15).

8. Conclusions

This report summarises recent findings on wind integration from the 16 countries participating in the International Energy Agency (IEA) Wind collaboration research Task 25 in 2012–14. The national case studies address several impacts of wind on power systems: long term planning issues and short term operational impacts.

The characteristics of **variability and uncertainty** in wind power are an important input to integration studies. There is a significant geographic smoothing effect in both variability and uncertainty of wind power when looking at power system wide areas. The smoothing effect can be seen in the measured extreme variations, and extreme forecast errors, that are relatively smaller for larger size areas. Variability is also lower for shorter time-scales. For day-ahead forecasts improvements up to 50% are expected by an aggregation of single wind power plants to region size like Germany. Offshore wind power will present more variability and uncertainty if a large part of wind power generation is concentrated to a smaller area. Power ramping in extreme wind events can be reduced by modifying the control of the individual wind turbines such that they continue producing at higher wind speeds, albeit at a reduced level. This will also improve the short-term forecasts of offshore wind power, which are critical in managing extreme storm situations.

The **grid reinforcement needed** for wind power is very dependent on where the wind power plants are located relative to load and existing grid infrastructure, and one must expect results to vary from country to country. Not many studies report the costs of grid reinforcements caused by wind power, as transmission lines in most cases will be used for multiple purposes. The national studies reported in recent studies address also flexibility needs mitigated through transmission to reduce curtailments of wind power, and to access flexibility from hydro power. The large offshore plans in Europe have launched research on offshore grids. It is evident from several studies that long term strategies for the development of offshore grids between several countries should be done in a coordinated way to ensure optimal developments.

Wind power's contribution to the system's generation capacity adequacy is its **capacity value**. Wind power will provide more capacity and thus add to the reliability of the power system. However, the benefits of added capacity vary depending on how much wind resource is available during times of peak loads. The capacity value of wind will decrease as wind penetration increases. The results show that most countries have a capacity value of 20–35% of installed capacity for the first 5–10% share of wind. However, for 20% share of wind in the system the capacity value is above 20% of installed capacity only for one study assuming a very large interconnected system. Aggregation benefits apply to capacity value calculations – for larger geographical areas, the capacity value will be higher. Also a large range can be seen for a same share of wind: from 40% in situations where high wind power generation at times of peak load prevail to 5% if regional wind power output profiles correlate negatively with the system load profile (often low wind power generation at times of peak load).

The impact of wind power on **power system dynamics** is becoming increasingly apparent with larger shares of wind power, and it will become more important to study in wind integration studies. Wind generation, by its mere presence, does not necessarily worsen the stability of a system, but it does change its characteristics, as it is increasingly connected via power electronics interfaces. Possibilities to support the grid by wind power plants have also been taken into account in more recent work. Results of transient stability after faults for up to 40% share of wind in the system show that this is not a challenging issue. For voltage stability using wind power plant capabilities will be crucial. Frequency stability challenges depend on system size, share of wind power and applied control strategies. This was first studied in smaller systems such as Ireland, but is increasingly being studied for larger areas with higher shares of wind power. Frequency drops can be significant in cases of high level of wind and solar energy, and studies of wind power providing very fast response to help the system are ongoing.

The impact of wind power on **reserve requirements** has been the focus of many integration studies for decades. The reserves are operated according to total system net imbalances, for generation and demand, not for each individual source of imbalance. There is a large range of results for estimates of increases in reserve requirements. The forecast horizon time-scale is a crucial assumption when determining how much reserve needs to be allocated, because the uncertainty of wind power will reduce more significantly than uncertainty of demand at shorter time-scales:

- If only hourly variability of wind and load is taken into account when estimating the increase in short-term reserve requirement, the results for most studies are 3% of installed wind capacity or less, with wind shares of up to 20% of gross demand.
- When 4-hour forecast errors of wind power and load are taken into account, an increase in short-term reserve requirement of up to 10% of installed wind capacity has been reported for penetration levels of 7–20% of gross demand.
- When day-ahead uncertainties are taken as basis of reserve allocation, wind power will cause increases of up to 18% of installed wind power capacity.

These increases in reserve requirement are calculated for the worst case. However, this does not necessarily mean new investments for reserve capacity. The experience so far is that wind power has not caused investments for new reserve capacity. New studies for higher shares of wind energy are increasingly looking at dynamic allocation of reserves: if allocation is estimated once per day for the next day instead of using the same reserve requirement for all days, the low-wind days will make less requirements on the system. The time steps chosen for dispatch and market operation can also influence the quantity and type of reserve required for balancing. For example, markets that operate at 5-minute time steps, can automatically extract balancing capability from the generators that will ramp to fulfil their schedule for the next 5-minute period.

Experience of **wind power curtailments** shows that curtailments do not occur in smaller shares of 5–10% of yearly electricity consumption, if there are no severe transmission bottlenecks and wind power is dispatched first among the low marginal cost generation. However, in some countries substantial curtailments (10–20% of wind generation) started occurring at lower shares of wind. The mitigation efforts regarding transmission build out in these countries have resulted in a reduction in curtailment rates with increasing wind power. Estimating future curtailments of wind energy as well as mitigation options to reduce them is emerging as one key result in integration studies. Wind power generators participation in the frequency control (ancillary services market) will decrease the overall curtailed renewable generation with large shares of wind power in the system, as this will allow other generation to shut down and make room for more wind power.

Balancing cost has traditionally been the main issue that many integration studies are trying to estimate. It is becoming less of an issue in countries where experience of wind integration is cumulating. Analyses regarding integration costs evolve towards comparing total system costs for different future scenarios, showing both operational and investment costs. In countries where wind power is out in the markets, balancing is paid by the operators in imbalance costs. There is some experience on the actual balancing costs, recorded for the power systems with growing shares of wind power. In Italy the costs have almost doubled, whereas in Germany, balancing costs have actually reduced by 50% despite growing share of wind and PV, due to the more profound impact of sharing balancing resources with the balancing areas.

Increased balancing due to **thermal power plant cycling** has been studied in detail to confirm that cycling costs are relatively small, compared to the reduction in operating cost that can be achieved with wind/solar energy. The impact on emissions is also very small. Wind power will reduce emissions for about 0.3–0.4 $MtCO_2/MWh$ when replacing mainly gas and up to 0.7 $MtCO_2/MWh$ when replacing mainly coal powered generation.

Measures to enhance the balancing task with high shares of wind power include operational practices and markets, demand side flexibility and storages. Electricity markets, with cross-border trade of intra-day and balancing resources; and emerging ancillary services markets are seen as a positive development for future large penetration levels of wind power. Energy system integration between electricity, gas and heat sectors is studied for future high share renewable systems. Enhancing use of hydro power storage to balance larger systems is another promising option. Electricity storage is seeing initial applications by system operators in places with limited transmission. Electricity storage is still not as cost effective in larger power systems as other means of flexibility, but different forms of storage have a large role in the emerging studies for 100% renewable systems. Integration studies for >40% shares of wind and solar power in the power system are pushing the limits of how much variable generation can be integrated. The results so far are promising and the work is on-going with more detailed modelling possibilities in future.

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Appendix: National research plans for wind integration in 2015–2017, Task 25 collaboration

National project contributions from Task 25 work plan (April 2015).

Canada: Hydro-Quebec is working on the following topics:

• Coordinating a global R&D approach to the integration of environmental risks in its operations from observation/forecasting to system management processes

• Improving its operational centralized wind power forecasting system that covers from real time operation to 10 days. This will include the uncertainty estimation taking into account the imminent meteorological conditions.

• Improving its methodology to dynamically define the needed balancing reserves, along the horizon of 1–48 hours and more, taking into account the compounded wind, load and other variable inputs forecast uncertainty, allowing for an optimal dynamic reserves level to be set corresponding to an acceptable level of risk, including allowance for the scheduling of generating unit outages and energy transactions. In order to incorporate dynamic reserves, IREQ is developing a stochastic unit commitment (UC), among others as a research project in collaboration with IBM. If proved successful, the potential for the replacement of the actual merit order UC will be assessed. Efforts will be made to link and quantify "acceptable" risk levels corresponding to set reserves with their associate costs and revenues from export sales

• Improving and using its "full year at 1 to 5 minutes time steps" simulation model to define the requirements for additional ancillary services due specifically to the integration of variable generation in the electric system: regulating and load following reserves. The model, developed by IREQ, takes into account security and regulation rules of the transmission system provider

• Continuing the development of variable generation assets' electrical models for power system studies allowing analysis on possible interactions between series-compensated power system, real HVDC controls, and massive variable generation. Continuing the analyses of the impacts of wind and other variable renewable energy sources (solar) and distributed assets (electric cars, etc.) on the system. Exploring the potential grid support schemes from advanced coordinated control of these assets

• HQ is involved with many Canadian utilities and system operators and US ISOs in the ongoing Pan-Canadian study, with the aim to study globally increased wind penetration in Canada, with overview of cross US border effects

China: State Grid Energy Research Institute (SGERI) is working on grid expansion and flexible generation deployment for the better utilization of wind power. For the model development, multi-regional power system expansion planning model with high wind power penetration, short-time-scale probabilistic production simulation incorporated with wind power model and operation optimization in power system with high penetration of wind power will be studied.

• For the optimum deployment of energy resources in the nationwide, we will study the proper grid configuration and grid planning in China. Planning of new flexible generation and its coordination in capacity, distribution and operation with wind power and other kinds of RE generations will be researched in depth.

• Developing probabilistic production simulation model that will mainly consider the uncertainty of wind power. This will include new algorithm for production simulation which can describe the variability of wind power better.

• Investigate and research on economic and technologic impact on hybrid AC and DC power system with the rapid growth of wind power in China.

• Operation optimization method developed for enhancing the operational flexibility in power system with large amount of wind power, and its objective is to promote more efficient utilization of installed wind power. This include more flexible control of interconnection lines, more larger balancing area control, adjustment of unit commitment, economic dispatching under consideration of large-scale wind power, coordination between thermal power, hydro power and wind power, etc.

• Research on the coordination between thermal power, hydro power and wind power in Northwest China, and build the models of upgraded dispatching pattern for better utilization of wind power.

• For the better utilization of wind power, some technologic and managing means have been proposed from sides of generation, grid and consumption, for examples, conjoint exploitation and operation of thermal power and wind power, demand side response etc., to the reasonable application of these means, we plan to investigate their capability for enhancing the integration of wind power and the corresponding economic and environmental benefits and costs.

Denmark: DTU Wind is working on the following topics:

• Tools and methods for representing wind power variability and uncertainty in power system reliability

• Wind power plant control

• Ancillary services from wind power plants

• Integration of wind energy in power system defence plans

• Inclusion of wind power uncertainties in power system reliability assessment

• RES grid integration studies, combining market with dynamic models

• Tools for representing combined wind and solar variability and uncertainty

• Methods for dynamic reserves accounting for wind power uncertainty

Energinet.dk will share the results of the TSO-task of preparing the Danish power system for 50% wind power penetration by 2025 (50% of domestic consumption delivered by wind):

• The challenges of operating a wind power dominated power system without conventional power stations on line (how to provide inertia, sufficient short circuit power, and continuous voltage control when power flow changes direction on tie lines and dynamic voltage support during and after faults).

• Capability of wind power plants to provide ancillary services

• Methods for planning of new transmission lines in power systems with a large wind power share

• Inclusion of the heat sector (heat pumps), the transport sector (electric vehicles) and the gas sector (gas production by electricity) into power system planning. The objective is to create additional flexibility, storage and balancing opportunities. Besides, new transmission lines abroad will increase the ability to accommodate more wind.

• Reporting from the Danish work on a new Market design for solving flexibility issues

• Reporting from the ENTSO-E collaboration on European Transmission System development. Wind continues to be one of the important triggers for grid investment needs in ENTSO-E's TYNDP (Ten Years Network Development Plan).

• Reporting from the ongoing EC projects Garpur (objective: define new classes of reliability criteria able to quantify the pan-European electric power system reliability in coherence with its evolution towards and beyond 2020); Ecogrid (Smart Grid implementation on the Danish island of Bornholm); E-Highway 2050 Project

France: EDF R&D, the research centre of Electricité de France (EDF), is working on the following topics:

• Methodologies and tools to support the operation of systems with variable generation:

• Development of probabilistic tools for quantifying the impact of wind and PV forecast errors on operation margins and reserve requirements and its application to the definition of dynamic reserve requirements;

• Development and application of probabilistic tools for the assessment of flexibility adequacy of power systems, for different time-scales (from day-ahead to 30 min ahead).

• Dynamic stability of power systems with high penetration of non-synchronous generation

• Participation of wind generation to ancillary services and synthetic inertia in large interconnected systems;

• Methodologies and tools to study the long term impacts of the integration of wind and PV on the European electricity system:

• Experiences with the development and implementation of methodologies to address operational issues in long terms planning tools for large interconnected systems: EDF R&D chain of tools includes dynamic stability and near term flexibility assessment in the long term generation planning across several interconnected systems.

• Methodologies for cost benefit analysis of flexibility sources such as storage, demand side management and interconnections;

• Economics of electricity systems with large penetration of VG:

• Integration of variable generation (wind and PV generation) into electricity markets: market price depression and revenue cannibalisation effects;

• Challenges for conventional generation: investment in backup capacity, decrease of revenues in energy only markets and opportunities represented by growing ancillary services and reserves markets;

• Wind participation in markets: strategies for minimising imbalance costs for variable generation producers;

Finland: VTT Technical Research Centre of Finland Ltd is working on the following topics (projects):

• impact of prediction errors of wind to Finnish and Nordic power system balancing (Icewind)

• impact of wind power on the Nordic energy balance, spot and balancing market prices and adequacy of balancing power, impact of flexibility options in the power system (FLEXe)

• value of DC transmission links in the Baltic/North sea (OffshoreDC)

• power to gas as flexibility option for integrating variable generation (NeoCarbon)

• flexibility from thermal power plants and from heat use and production (FLEXe)

• improving the optimisation of storage use and other longer time-scale decisions utilizing up to 2-week calibrated stochastic energy forecasts from mesoscale models (VaGe)

Germany: Fraunhofer IWES is working on the following topics:

• Development of innovative weather and wind and PV power forecast models for the grid integration of weather dependent energy sources (http://www.projekt-eweline.de/en/index.html):

• Extreme forecast errors

• Provision of ancillary services with wind energy and PV

• Characterization of wind and PV power production on different aggregation levels and interaction between wind energy and PV

• Available Active Power Estimation

• Dynamic methods for setting electricity system operating reserve

• Simulation of the electricity supply system with a high share of RES

• Investigation of ways to a 100% renewable electricity system

• Renewable virtual power plants

• Market design with respect to a large-scale integration of RES

• Definition of data requirements for a secure power system with high shares of RES

The Research Center for Energy Economics (FfE) is working on the following topics:

• Spatially resolved RES expansion and its impact on grid an storage requirements

• Provision of ancillary services from devices located in the distribution grid

• Demand for grid extension

• Storage demand

• Analysis of hindrances arising from market design

Ireland: Electricity Research Centre (ERC) at University College Dublin and Trinity College Dublin is working on the following topics:

• Development of operational & planning tools and strategies for the integration of high levels of wind energy

• Dynamic stability of power systems with high penetration of non-synchronous generation

• Demand-side and storage options for enhancing power system flexibility

• Design of market mechanisms and ancillary services suitable for systems with high wind penetrations

• Development strategies for forecasting and utilising ancillary services from wind generation.

Italy: Terna Rete Italia, the company of the Terna Group that deals with the national electricity grid's operation, maintenance and development, is working on the following topics:

• Presentation of the actual critical operation conditions already experienced and measures to solve them

• Procedures for reserve requirement assessment

• Assessment of risk of "overgeneration" and needs for downward generation capacity

• Impact of new storage devices for solving local overloads and/or system balancing

• Role of active demand for balancing, contributing to frequency regulation or providing reserve

• Transmission system expansion facing large amounts of wind power and distributed PV generation

• Ancillary market design and operation with high penetration levels of wind power and distributed PV: possible markets models and experiences.

Japan: Tokyo University of Science and Kansai Universities and Criepi are working on the following topics:

• Capacity value of wind and photovoltaic power generation including the impact of the difference of the peak demand period (the difference of the area) will be evaluated.

• The characteristics of load with large amount of renewable integration; Regulating and operating reserves to accommodate renewable integration; Analytical approaches and simulations including long-term power supply planning, pumped storage hydro power operational planning, unit commitment and load dispatching control, simulation of sub-hourly operations, real-time frequency controls, etc.; The impacts to grid operations if renewable energy goals over 2030 are achieved or exceeded; Recommendations for possible facilitation/mitigation measures to large amount of renewable integration.

Mexico: IIE (Instituto de Investigaciones Electricas) is working on the following topics:

• Enhance features of PEGYT Model (IIE Generation and Transmission Expansion Planning Model) that has been used in Mexico for the long term generation planning process, in order to consider seasonal properties and diurnal distributions of both wind and solar generation for each country region.

• Long term capacity generation and transmission expansion planning for Mexico, considering the penetration goals of clean energies established in Mexico Laws.

• Simulations of short term Mexican system operation, considering 2016-2024 scenarios of high growth in electric load and high growth in wind and solar generation capacity, in order to evaluate system flexibility requirements.

Netherlands: TenneT TSO b.v. is working on the following topics:

• What is the minimum online conventional generation needed in order to have a secure grid in the case of an incident, at high wind penetrations.

• Investigation of the problem and possible solutions for resonance phenomena that can be encountered at low frequencies, such as 100 Hz, in the vicinity of AC cables connecting offshore wind to the onshore grid.

• How to model the short circuit contribution coming from distributed generation.

• Transmission planning methods: round-the-year security analysis, experience with implementing and using the method.

• EU project GridTech (Innovative grid-impacting technologies enabling a clean, efficient and secure electricity system in Europe)

• EU project Umbrella (developing an innovative toolbox to support the decentralised grid security approach of TSOs)

• EU project Low Inertia Systems

• National projects in collaboration with Dutch universities (TU Delft, TU Eindhoven, RU Groningen, VU Amsterdam) The 380 kV cable project; FLOW (Far and Large Offshore Wind) project on Dynamic Power Management; FLOW on system stability and grid code requirements; Reliability of offshore and onshore electricity systems with large scale wind; INCAH ; NWO URSES WAMPAC on PMU supported corrective control; NWO URSES DISPATCH distributed intelligence; TKI Wind at Sea on Synergies at Sea ; VDE Stability of sustainable power systems with high penetration DER ; NWO Offshore transnational Electricity Infrastructure, design, operation, regulation; NWO Top Sector (potential: Redesign Electricity Markets).

TU Delft is working on the following topics:

• Impacts on system stability and grid code compliance

• Transnational Electricity Infrastructure

• Reliability of EHV lines

• Integration of Offshore RES through VSC-HVDC Multi-terminal Transmission Grids

• Comprehensive reliability assessment (GARPUR project)

• Stability of sustainable power systems with high penetration of DER

• Planning and control of HVAC-HVDC systems

• Massive integration of power electronic converter technologies
• Identification of dynamic equivalents for RES

Norway: SINTEF is working on the following topics:

• Utilisation of the flexibility of the Nordic hydro power based power system, to balance wind power variation in the North Sea region. Special focus is put on offshore wind power plants.

• Investment strategies of offshore grids for offshore wind power plant grid integration and better market coupling in the North Sea region.

• Socio-economic benefits and costs of offshore grids and its impacts on power system control and market operation

• Developing a new market concept using smart grid solutions to be responsive to imbalances caused by variable wind production

• Assessment of the technical implications on the electric power systems caused by large shares of wind power and the resulting flows on the network.

• Electric power system support by wind power plants through grid codes and ancillary services.

• Grid integration technologies for large amounts of remote offshore wind power plants, which pose a challenge due to their distance from shore.

Portugal: LNEG, FEUP/INESCTEC and the Technical University of Lisbon/IST are working on the following topics:

• Virtual Renewable Power Plants (VRPP): (LNEG) Correlation of renewable distributed resources, assessment of the excess of renewable energy generation and need for added energy storage capacity both on large/national and small/local bases (e.g. pumped hydro, VRB batteries and plug-in vehicles). Development of VRPP dynamic and stationary models for application in power system stability studies, and local network congestion. for the characterization of the VRPP technical and economic benefits. (LNEG) Development of decision-support tools based on stochastic optimization for VRPP managers in order to boost their market integration). Storage Systems and Electric Vehicles. (LNEG) Assessment of the impact of EVs, domestic DGs and smart battery energy storage solutions in the local grid power quality. Local characterization of THD, flicker and voltage profiles. (INESC TEC/FEUP) HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies (HYPERBOLE – FP7 EU project, 2013–2016). Enhanced hydropower plant value by extending the flexibility of its operating range, while also improving its long-term availability, including fixed and variable speed models. More specifically, INESC TEC/FEUP will conduct electric network integration studies, in which the optimal integration of renewable energy in the electric network will be studied, on the basis of the extended operating range and flexibility of hydro- and pumped storage power plants.

• Transmission Tools for Large Wind Integration: (LNEG) Analysis of wind power contribution to manage grid congestion based on regional wind power clusters. (Project EU IRP Wind, 2013–2017). (INESC TEC/FEUP) Innovative tools for the future coordinated and stable operation of the pan-European electricity transmission system (FP7 EU Project iTESLA, 2012–2015). Procedures for service restoration with large-scale wind power in transmission grids. High Voltage Direct Current (HVDC) technology for offshore grid development. COMUTE-DC: Control and Operation of Offshore Multi-Terminal DC grids (FCT Project, 2013–2015). This project aims the identification and development of innovative control functionalities to run autonomously at Multi-Terminal DC (MTDC) converter stations and offshore wind farms. A key development of the project regards the possibility of exploiting inter-area frequency regulation services and even inertial emulation and primary frequency control from offshore wind farms. Additionally, the development of control solutions regarding the provision of AC-side FRT capability from MTDC grids. A reduced scale laboratorial prototype of a 4 terminal MTDC grid is proposed to be specified and developed, making possible the demonstration of key project developments such as frequency control functionalities

• Advanced wind power forecasting algorithms: (LNEG) Develop a circulation weather pattern modelling system to search for atmospheric conditions that increase numerical weather forecast uncertainty (IRP Wind), (LNEG) Upscaled forecast based on wavelets and multivariate statistical decompositions (IRP Wind). (LNEG) Automatic detection of wind ramps and extreme wind events with drastic impacts on the power system by the characterization of synoptic weather regimes and their transitions. (FCT Fluctwind – characteristics of ramps and fluctuations).

• Operating Reserves; (LNEG) Development of a methodology for rational use of dynamic reserves based on the forecast of extreme wind events. (LNEG) Access the contribution of coordinated wind power clusters and storage assets in providing balancing services (FP7 IRP Wind).INESC TEC/FEUP and TSO REN: direct contract (2015) for operationalization of a tool that estimates the operating reserve requirements in systems with high penetration of renewable energy. This tool will include uncertainty from different sources, such as load, conventional power plants, wind, solar, CHP, mini-hydro

• Markets: (LNEG) To address the challenges of using software autonomous agents to help manage the complexity of electricity markets, particularly:Pool markets and the associated technical and economic issues, notably issues related to auction mechanisms (Project EU IRP Wind, 2013-2017). Forward markets and the associated bilateral trading process, mainly the negotiation of the key terms of bilateral contracts (price, amount of energy, duration, etc.) (FCT project MAN-REM) (LNEG) To model power generating companies as software agents able to trade energy in different markets, notably pool and forward markets, placing emphasis on their decision-making process, typically affected by several uncertainties (e.g. power plant outages, uncertain market prices for electricity, imperfect wind power forecasts, etc.) (Project IRP Wind). (LNEG) To model wind power plants clusters as coalitions of software agents, able to participate in liberalized electricity markets. To develop specific case studies (Project EU IRP Wind, 2013–2017).

Spain: UCLM-IER (Universidad de Castilla-La Mancha/Instituto de Investigación de Energías Renovables) is working on the following topics:

• Integration of renewable energy power plants in power systems under the new international standards: development and validation of electrical models for wind and solar resources

• Frequency control in smart grids with large amount of wind power

• Power fluctuations of wind power plants: analysis and regulation

• Variable generation plant modelling. Studies of power systems with large amount of variable energy wind power: storage and electric vehicles

Sweden: Royal Institute of Technology, Kungliga Tekniska Högskolan, KTH, is working on the following topics:

• intra-hour balancing of wind power (PhD student Camille Hamon)

• hydro scheduling with large amounts of wind power (PhD student Yelena Vardanyan)

• market design for efficient balancing with large amounts of wind power (PhD student Richard Scharff)

• solar power integration (post doc Afshin Samadi)

• use of CHP as a balancing resource is systems with large amounts of wind power (PhD student Ilias Dimoulkas)

• primary and secondary control issues with multi-terminal HVDC off shore systems with wind power

• Smart Grid Applications in households and their role in a system with large amount of wind power (new PhD student: under recruitment)

• Studies of Sweden based on close to 100% renewable energy (Lennart Söder + plan to recruit a new PhD student)

• General studies of application of new storage techniques in power systems with large amount of wind power (new PhD student: Dina Khastieva)

UK: The UK Centre for Sustainable Electricity and Distributed Generation (SEDG) will be the focal point of the UK participation in the Task, with Imperial College and Strathclyde as participants. Key areas of work which were planned for Task 25 Phase 3:

• Enhancement of methodologies to analyse system operation and development of systems with large scale penetration of wind considering the need for generation and demand, storage and the role and value of interconnections.

• Assessment of transmission requirements for integration of large scale on- and off-shore wind generation.

• Investigation of the interactions between generation reserve allocation and transmission investment.

• Review of the deterministic and probabilistic transmission network security standards in the context of cost effective integration of wind generation.

• Understanding of the challenges to operate and design hybrid on- and off-shore shore transmission networks in light of the public opposition to onshore transmission.

• Investigation of alternative regulatory approaches that would facilitate anticipatory investment in transmission to enable timely connection of wind generation

• Evaluation of various transmission pricing approaches and their impact on network and generation investment (conventional and wind).

• Analysis of alternative approaches to incentivising the investment in peaking and flexible plant in systems with significant penetration of wind generation.

USA: NREL is working on the following topics:

• Market design. NREL is comparing various market approaches to incentivize flexibility in RT markets. We are also evaluating revenue sufficiency longer-term, at various wind (and solar) penetration rates.

• Flexibility analysis. To evaluate the value of various flexibility options collectively and separately.

• New multi-year data sets of wind power and work related to capacity value of wind power. NREL LOLP tool, REPRA, can be circulated to the IEA T25 participants for making some international comparisons.

• Linking AGC and Unit Commitment models/simulations (FESTIV; code sharing possible)

• Dynamic studies

• Hydropower flexibility and wind integration

• Active power control from wind turbines and wind power plants

• Large scale studies combining interconnections; higher shares VG

EWEA (now WindEurope): WindEurope will review relevant integration studies and policies relevant for wind power integration at the European level, with focus on the following topics:

• System operation at European level with large amounts of wind power including cluster tools for power output aggregation and operation;

• Value of new flexibility measures: more specifically advances in ancillary services provision with wind energy and associated market designs and products;

• Requirements, standards and grid codes for connection, balancing and congestion management of wind generation at European level;

• Balancing costs experienced by wind generators at European level;

• Upgrade of the transmission system for large amounts of wind power especially the case of offshore grids and electricity highways used in international exchange and trade;

• Design of efficient electricity markets with large amounts of wind power

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Title	**Design and operation of power systems with large amounts of wind power** Final summary report, IEA WIND Task 25, Phase three 2012–2014
Author(s)	Hannele Holttinen, Juha Kiviluoma, Alain Forcione, Michael Milligan, J Charles Smith, Jan Dobschinski, Serafin van Roon, Jody Dillon, Nicolaos Cutululis, Antje Orths, Peter Børre Eriksen, Enrico Maria Carlini, Ana Estanqueiro, Ricardo Bessa, Lennart Söder, Hossein Farahmand, Jose Rueda Torres, Bai Jianhua, Junji Kondoh, Ivan Pineda & Goran Strbac
Abstract	This report summarises recent findings on wind integration from the 15 countries participating in the International Energy Agency (IEA) Wind collaboration research Task 25 from 2012–2014. Both real experience and studies are reported. The national case studies address several impacts of wind power on electric power systems. In this report, they are grouped under long-term planning issues and short-term operational impacts. Long-term planning issues include grid planning and capacity adequacy. Short-term operational impacts include reliability, stability, reserves, and maximising the value of wind in operational timescales (balancing related issues). The first section presents the variability and uncertainty of power system-wide wind power, and the last section presents recent wind integration studies for higher shares of wind power. Appendix provides a summary of ongoing research in the national projects contributing to Task 25 from 2015–2017.
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