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IEA Wind Task 25 - summary of experiences and studies for wind integration

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***Abstract*— IEA WIND R&D Task 25 on "Design and Operation of Power Systems with Large Amounts of Wind Power" collects and shares information on wind generation impacts on power systems, with analyses and guidelines on methodologies. The summary report published June 2016 contains summary of experience of wind integration as well as the most relevant wind power grid integration studies in the 16 participating countries. The studies address concerns about long-term planning issues and short-term operational impacts. There is already significant experience in integrating wind power in power systems. Electricity markets, with cross-border trade of intra-day and balancing resources, and emerging ancillary services markets are considered as a positive development for future large shares 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. 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 ongoing with more detailed modelling possibilities in the future. 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.**

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION

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 (IREQ), China (SGERI), Denmark (DTU and Energinet.dk), Wind Europe (formerly EWEA), Finland (VTT), Germany (Fraunhofer-IWES and FfE), Ireland: (SEIA and UCD), Italy (Terna), Japan (Universities of Kansai and Tokyo and CRIEPI), Norway (SINTEF), the Netherlands (TenneT and TUDelft), Portugal (LNEG and INESC-TEC), Spain (UCLM), Sweden (KTH), United Kingdom (Imperial College London and Strathclyde University), United States (NREL, UVIG and DoE).

The existing targets for wind power anticipate a high share 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. 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.

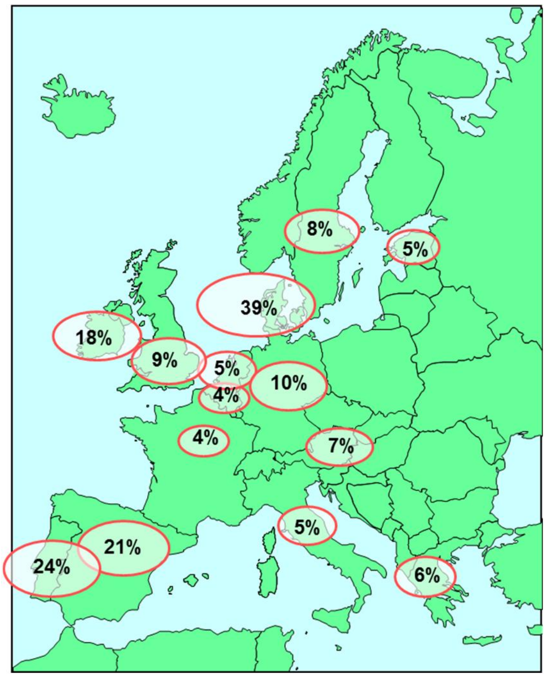

Figure 1. Wind generation share of total electricity consumption in 2014 in European countries

The share of wind energy is usually depicted as share of energy (annual wind energy generated divided by total annual electricity consumption), which gives a better idea than the capacity share (installed wind capacity divided by peak load). A more complete picture of the integration challenge is given by a metric dividing installed wind capacity with minimum load and export possibilities of electricity (Figure 2).

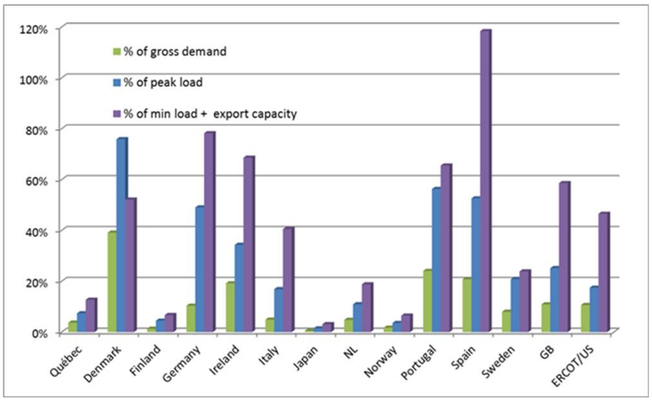

Figure 2. Wind share in the studied countries and areas, measured in three ways: wind generation as share of electricity consumed (% of gross demand), wind capacity as share of peak load capacity and wind capacity as share of minimum load plus export capacity (European countries as maximum hourly day-ahead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

IEA Wind Task 25 has produced a series of reports on the state-of-the-art knowledge and results that had been gathered so far for wind integration [1][2][3][4]. All of these reports are available on the IEA Wind Task 25 website: http://www.ieawind.org/task_25.html#.

This article summarises the results of the latest report from June, 2016 [4]. Both actual experience 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. These impacts 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 report also presents the variability and uncertainty of power system-wide wind power, and recent wind integration studies for higher shares of wind power.

II. VARIABILITY AND UNCERTAINTY OF WIND POWER – AN IMPORTANT INPUT

It is important to have as an input to integration studies data for aggregated wind power covering larger regions, like balancing areas or the whole synchronous system. 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.

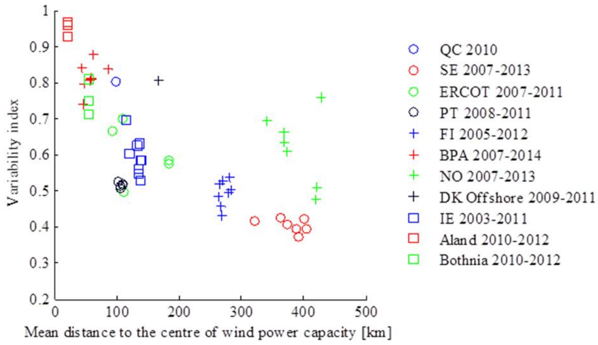

Figure 3. Variability index versus the mean distance to the capacity weighted geographical centre of wind the analysed wind power fleet. As dispersion grows, variability decreases [5].

The smoothing effect is shown in the measured extreme variations and extreme forecast errors, which are relatively smaller for larger areas – examples of these from real data has been collected in the report [4] . Figure 3 shows how the variability is reduced when the size of the area is larger. Variability is also lower for shorter timescales. It has been found that there is a close to linear relationship between variability and predictability [6]. 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.

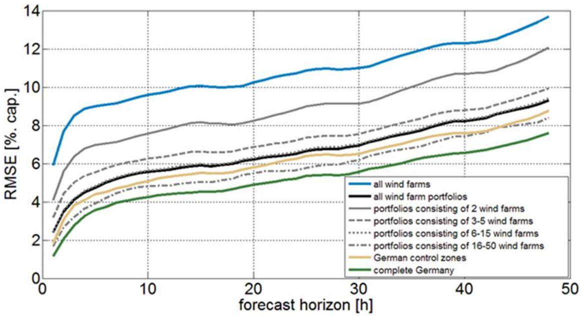

Figure 4. Forecast accuracy depending on the forecast horizon (as root-mean-square-error RMSE in percent of the installed wind power capacity). The lines present different aggregation levels ranging from single wind power plants (blue) up to complete Germany (green). The forecast accuracy has been averaged over several relevant wind power plants, wind power plant portfolios and over all 20 different weather forecasts [6].

If offshore wind power is built so that a large part of wind power generation is concentrated in a smaller area, it will present more variability and uncertainty than what we are used to see from on-land wind power. 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.

III. WIND POWER IN LONG TERM PLANNING FOR GRID AND GENERATION ADEQUACY

A. *Grid reinforcement due to wind power*

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 [7]. In Sweden a similar categorization was used [8]

In the USA recent reports highlight the transmission build out for Minnesota area for up to 50 % wind share [9], as well as total USA reaching 90 % renewable share in electricity sector [10][9].

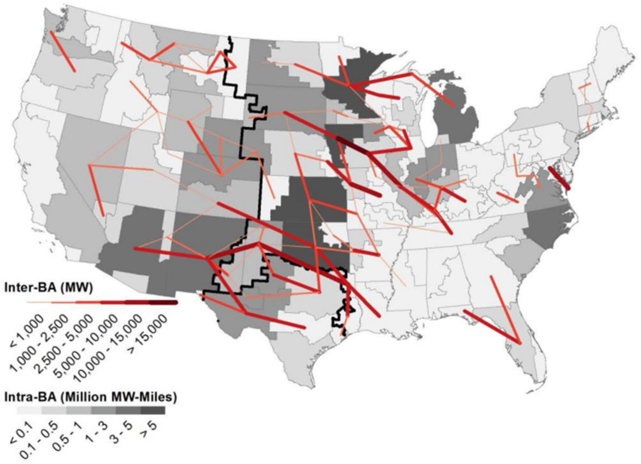

Figure 5. Conceptual transmission map from REF Study showing intra and inter Balancing Area for transmission network reinforcements needs for high renewables future [10].

The national results reported in China and Italy also address flexibility needs mitigated through transmission to reduce curtailments (Figure 6 for Italy). In Norway, transmission network is studied from the point of view of accessing flexibility from hydropower with high amounts of wind power in Northern Europe [11] (Figure 7).

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.

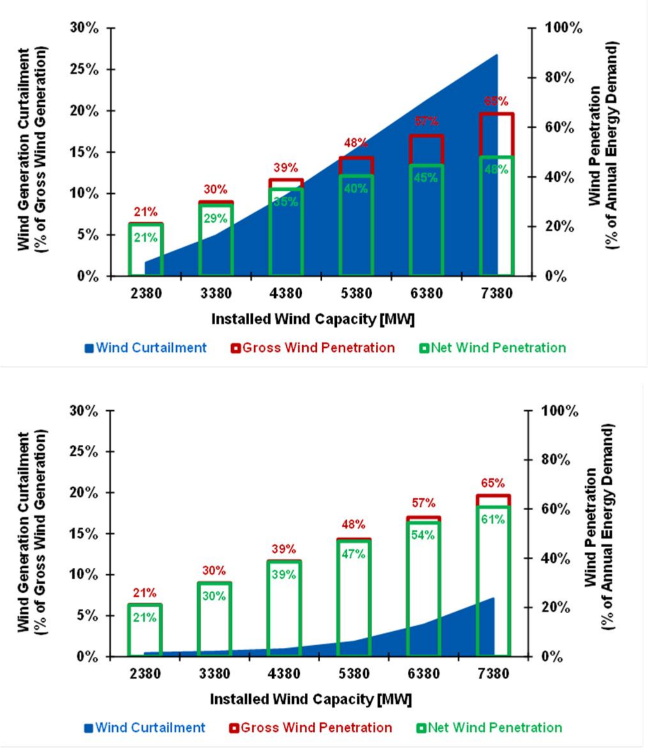

Figure 6. The development of exchange capacity with Sicily (new project Sicily Mainland) will reduce the curtailed wind generation (maximum curtailment equal to 7.1% in the analysed scenarios) and the gap between the real (net) and potential (gross) wind penetrations (Source: Terna).

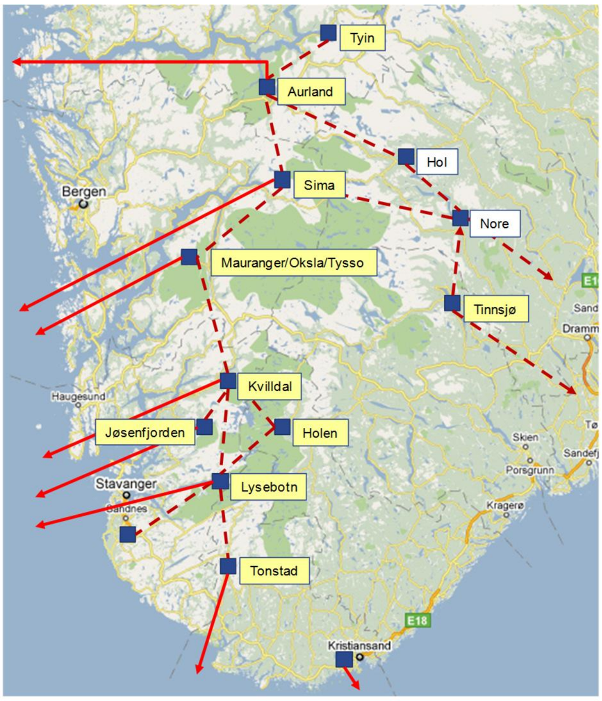

Figure 7. Interconnections needed to enable flexibility of Norwegian hydro power to be used for increased balancing needs of wind power around the North Sea [12].

B. *Capacity value of wind power*

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 capacity) 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 presented in Figure 8 are from the following studies, using different methodologies: Germany [13], Ireland [14][15], Norway [16], Quebec [17], UK [17], US New York [19], US Minnesota [20][21][9], US California [22], US EWITS study [24] and Finland [23].

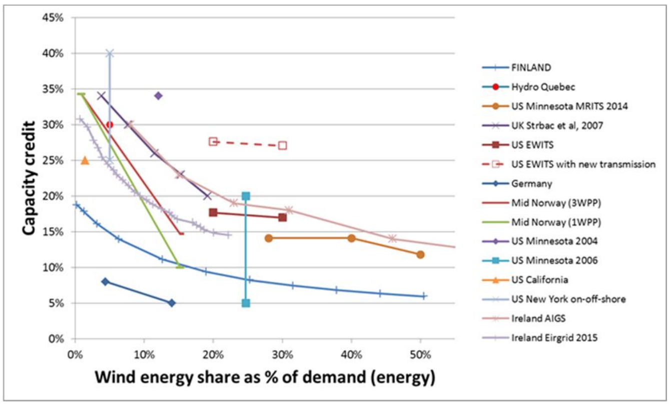

Figure 8. Capacity value (capacity credit) of wind power. Comparison of results from different analyses.

The results in Figure 8 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. As turbine towers have increased in height for the past several years, energy capture has increased and this can also have an influence on more recent capacity value assessments.

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).

IV. IMPACTS OF WIND POWER ON SHORT-TERM 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.

A. Stability impacts

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 defense 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, and this may even improve the stability situations.

Transient stability simulations for after-fault situations in the system show that this is not a challenging issue for up to a 40% share of wind energy. 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 (Figure 9). 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.

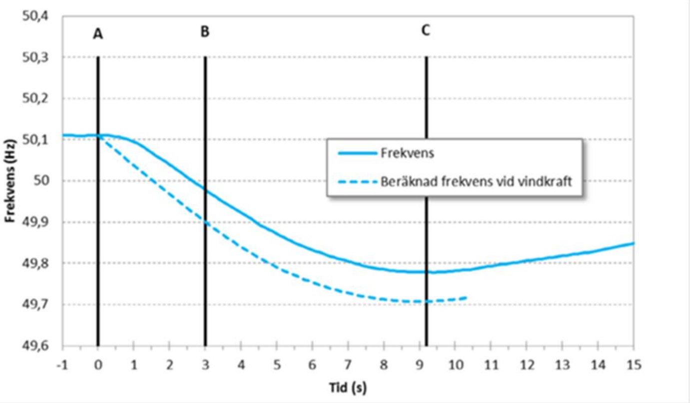

Figure 9. Frequency drop of the Nordic power system with 46600 MW load and assuming a 1400 MW trip off, with or without 7000 MW wind power (Frekvens = Frequency; Tid = Time; Beräknad frekvens vid vinkraft = Estimated frequency with wind power). [8]

B. Reserve requirements

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 updated summary from previous Task 25 summary reports is presented in Figure 10. The results presented for increase in reserve requirements due to wind power are from following studies: Canada/Hydro Quebec [25], Germany [13][26], Ireland [14], NL [27], UK [27], Sweden [29]. Nordic, Finland, Sweden, Denmark hourly variability [30], US/Minnesota [21], US/New England ISO [31].

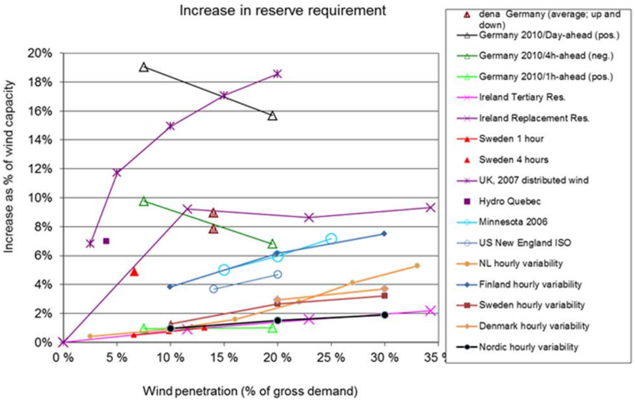

Figure 10. Summary of results from different studies for increase in reserve requirements due to wind power

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

V. 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.

A. *Minimising curtailments*

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 [32]. 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. The system value from wind and solar energy providing frequency support is increasing at higher shares of wind and solar energy (Figure 11).

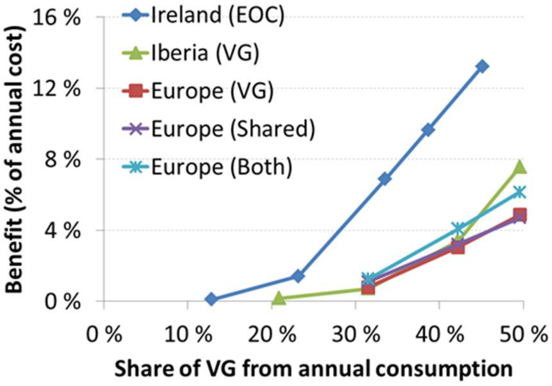

Figure 11. System benefits (decrease of annual operating costs) when introducing wind power and PV in frequency reserves will increase at higher shares of variable renewables [33].

B. *Balancing costs and cycling costs*

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 experiences 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 participating 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 [36] (Figure 12).

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 [33]. The full cycling from start to stop of coal power plants if moving from base load operation to market operation shown in Figure 13 for Minnesota, US, for two wind and solar shares.

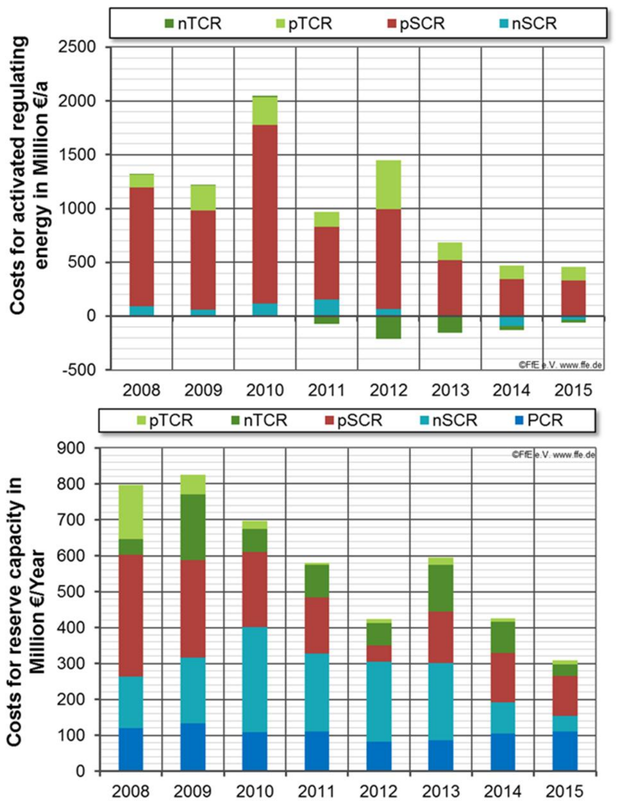

Figure 12. Cost of short term balancing in Germany – a decreasing trend despite increase of wind and solar generation, due to system operators collaboration. PCR Primary, SCR Secondary and TCR Tertiary control, p for positive and n for negative. Costs for activated energy (above) and reserved capacity (below) [4].

The impact of increased balancing task of fossil fuel powered plants on emissions is also very small. Wind power reduces CO2 emissions for approximately 0.3–0.4 Mt/MWh when replacing mainly gas and up to 0.7 Mt/MWh when replacing mainly coal-powered generation [35].

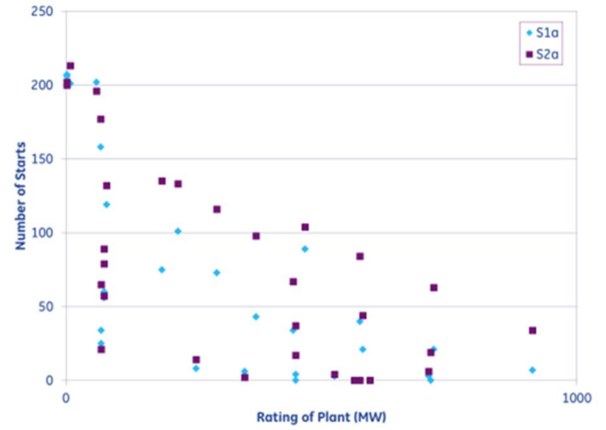

Figure 13. Annual operational starts of coal units in Minnesota due to economic commitment. Scenario 1a has 40% and Scenario 2a 50% wind and solar energy [9].

C. *Enhancing flexibility for integration*

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.

Enhancing the use of hydropower storage to balance larger systems is another promising option. Pumped hydro flexibility is already used today in many countries to manage high wind low load situations (Figure 14 case of Portugal). In Ireland the benefits of increasing pumped hydro storage are shown in Figure 15.

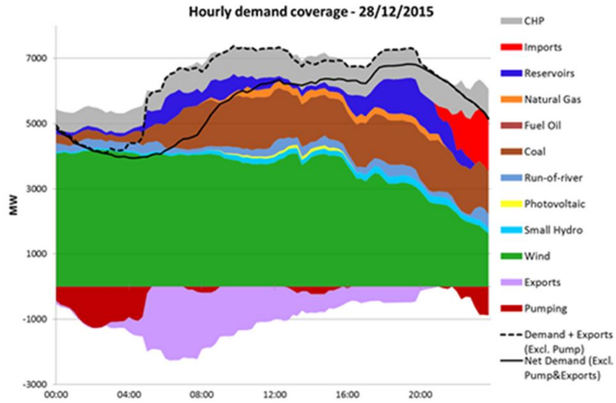

Figure 14. Incident where wind power production exceeded electricity consumption in Portugal, for a couple of hours during the night [4] (Source for data REN: http://www.centrodeinformacao.ren.pt).

Electricity storage is seeing initial applications by system operators in places that have limited transmission capacity, like Italy. 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.

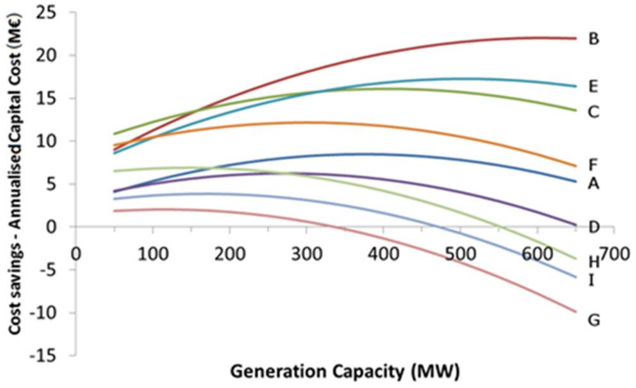

Figure 15. Benefits of pumped hydro storage in Ireland with increasing pumped hydro capacity in year 2025. The scenarios A…I are with different options of storage size (2 and 10 hours), installed wind and limit for instant wind penetration (50 or 75%). Most cost effective are the ones with only 2 hour storage (with high wind B, and medium wind E) [37].

VI. HIGH SHARE RENEWABLE STUDIES PUSHING THE LIMITS OF INTEGRATION

The results so far are promising from integration studies for higher share, >40 % of electrical energy from wind and solar energy. Large share studies have been published from Germany, Denmark, Sweden and USA. The work is ongoing with more detailed modelling possibilities in the future.

Energy systems integration among the electricity, gas, and heat sectors is studied for future power systems that have high shares of renewables, example from Denmark in Figure 16. In Denmark, 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 [38].

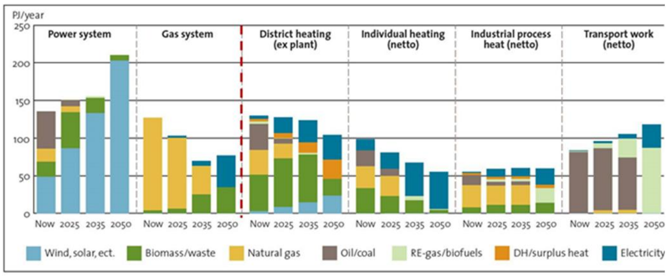

Figure 16. Possible Danish transition process: Left: production development. Right: future consumption development for different sectors [38].

VII. CONCLUSIONS AND DISCUSSION

This paper is a summary of the IEA WIND Task 25 recent report summarizing experience of wind integration as well as the most relevant wind power grid integration studies in the 16 participating countries. 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 concerns about 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 in operational time scales (balancing related issues).

There is already significant experience in integrating wind power in power systems. Electricity markets, with cross-border trade of intra-day and balancing resources, and emerging ancillary services markets are considered as a positive development for future large shares 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 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.

The characteristics of variability and uncertainty in wind power are presented from experience of measured data from large-scale wind power production and forecasting. The national grid studies address also flexibility needs mitigated through transmission to reduce curtailments of wind power, and to access flexibility from hydro power. The large offshore wind power plans in Europe have launched research on offshore grids.

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.

The impact of wind power on power system dynamics is becoming increasingly apparent with larger shares of wind power. Wind generation does not necessarily worsen the stability of a system, and possibilities to support the grid by wind power plants have also been taken into account in more recent work.

There is a large range of results for estimates of increases in reserve requirements, depending on forecast horizon time scale. New studies for higher shares of wind energy are increasingly looking at dynamic allocation of reserves.

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 ongoing with more detailed modelling possibilities in the future.

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 time scale is minimised. Estimating future curtailments of wind energy as well as mitigation options to reduce them is emerging as one key result anticipated in integration studies. 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.

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