EXPERT GROUP REPORT ON

RECOMMENDED PRACTICES

16. WIND INTEGRATION STUDIES

1. EDITION 2013

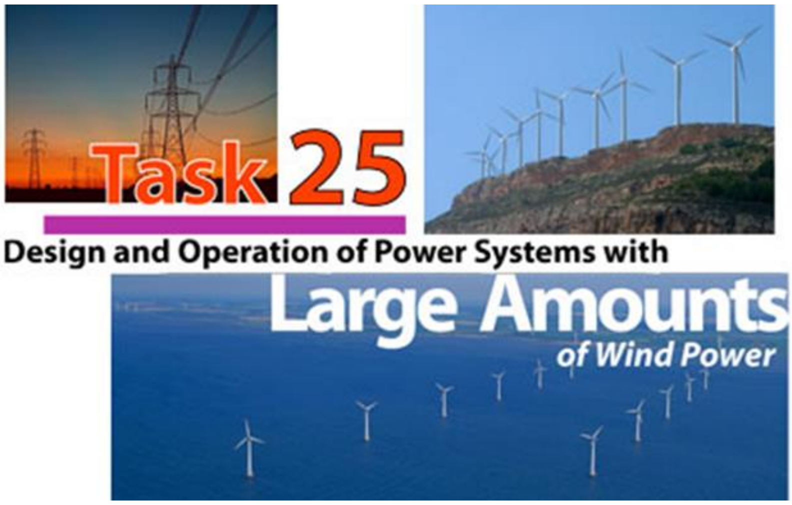
Submitted to the Executive Committee
of the International Energy Agency Implementing Agreement
for
Co-operation in the Research, Development, and Deployment
of Wind Energy Systems

Approved Sept. 12, 2013

EXPERT GROUP REPORT ON
RECOMMENDED PRACTICES

16. WIND INTEGRATION STUDIES

1. EDITION 2013



Edited by:

Hannele Holttinen

Technical Research Centre of Finland VTT

P.O. Box 1000, 02044 VTT

Finland

With contributions by:

- *Antje Orths, Hans Abildgaard, Energinet.dk, Denmark*
- *Frans van Hulle, EWEA*
- *Juha Kiviluoma, VTT, Finland*
- *Bernhard Lange, Fraunhofer IWES, Germany*
- *Mark O'Malley, Damian Flynn, Andrew Keane, Jody Dillon, UCD, Ireland*
- *Enrico Maria Carlini, Terna, Italy*
- *John Olav Tande, Sintef, Norway*
- *Ana Estanqueiro, LNEG, Portugal*
- *Emilio Gomez Lazaro, Uni Castilla la Mancha, Spain*
- *Lennart Söder, KTH, Sweden*
- *Michael Milligan, NREL; J.Charles Smith, UVIG; Charlton Clark, DoE, US*

…

FOREWORD

The International Energy Agency Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems (IEA Wind) is a vehicle for member countries to exchange information on the planning and execution of national, large-scale wind system projects and to undertake co-operative research and development projects called Tasks or Annexes.

As a final result of research carried out in the IEA Wind Tasks, Recommended Practices, Best Practices, or Expert Group Reports may be issued. These documents have been developed and reviewed by experts in the specialised area they address. They have been reviewed and approved by participants in the research Task, and they have been reviewed and approved by the IEA Wind Executive Committee as guidelines useful in the development and deployment of wind energy systems. Use of these documents is completely voluntary. However, these documents are often adopted in part or in total by other standards-making bodies.

A Recommended Practices document includes actions and procedures recommended by the experts involved in the research project. A Best Practices document includes suggested actions and procedures based on good industry practices collected during the research project. An Experts Group Report includes the latest background information on the topic as well as a survey of practices, where possible.

Previously issued IEA Wind Recommended Practices, Best Practices, and Expert Group Reports can be found at www.ieawind.org on the Task 11 web pages.

PREFACE

This Expert Group Report provides recommendations based on more than 8 years of work within International Energy Agency (IEA) Wind Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power. The report is issued as an IEA Wind Recommended Practices document to provide research institutes, consultants, and system operators with the best available information on how to perform a wind integration study. The recommendations will be updated as further work in IEA Wind Task 25 reveals improved integration study methodologies based on real wind integration experiences. The main findings in this report are applicable to other variable renewables, such as photovoltaics.

This Expert Group Report describes the methodologies, study assumptions, and inputs needed to conduct a wind integration study. Findings and results from previous wind integration studies are discussed in the two summary reports (Holttinen et al. 2009; and 2013).

The Task 25 Expert Group developed a flow chart that outlines the phases of a complete wind integration study (see Figure 1). The flow chart could also direct integration studies for other variable renewables, such as photovoltaics. Conducting a full study is a complicated process, especially taking into account all possible iteration loops. It may not be feasible or necessary for all integration studies to perform each phase included in the flow chart. The flow chart shows these relationships, and points out the importance of the study set-up assumptions to results. It also allows reviewers to understand what was completed in any particular study and what was not, providing a context for comparison.

The authors of this Recommended Practices are listed at the beginning of each section. Review comments have been received from: Canada: Maurice Huneault of the Institut de recherche d'Hydro-Québec (IREQ) in Canada (Ch2); Germany: Ralph Pfeiffer of Amprion GmbH; Italy: Laura Serri of RSE S.p.A.; United States: Stephen Beuning of Xcel Energy, Hua Ling of the Midwest Independent Transmission System Operator (MISO), Kevin Porter of Exeter Associates, Bruce Tsuchida of the Brattle Group, and Jonathan Ruddy from University College Dublin (UCD) is acknowledged for help in producing the flow chart.

This report will only describe the methodologies, study assumptions, and inputs needed for an integration study. The findings and results from integration studies so far are discussed in the 2007 state-of-the-art report and the final reports of the two 3 year periods (2009 and 2013) (Holttinen et al. 2007, 2009, and 2013).

Hannele Holttinen

Operating Agent, IEA RD&D Wind, Task 25

April 2013

NOTICE:

Executive Summary / Summary of Recommendations

Challenge

Many individual wind integration studies have been conducted in recent years. Wind integration studies typically simulate a future power system with wind contributions (penetration) varying from 5% to more than 20% of annual electrical supply. The studies seek to evaluate the impacts of wind on the grid and on the operation of power generation. The power systems being studied and the data available about them vary significantly. The methodologies used in these studies vary and are still evolving. Also the goals and approaches differ, and thus the results are difficult to compare.

The lack of reliable and comparable knowledge about the effects of integrating wind generation can limit large-scale development of wind power, due to uncertainties about its impact. With growing wind deployment and the tremendous potential for expanded wind generation capacity, it is crucial that commonly accepted methodologies are applied to accurately assess integration issues. Until now, there have been no Recommended Practices / Best Practices available to guide the conduct of wind integration studies. This report gives the current view of recommended methodologies, in a still evolving field, pointing out also future development needs.

Approach

The purpose of this report is to provide research institutes, consultants, and system operators with the best available information on how to perform a wind integration study. The findings are based on the more than 8 years of international collaboration under IEA Wind Task 25, with experts sharing experience and challenges in their national studies. The experts have outlined the phases of a complete integration study and illustrated this in a flow chart (Figure i). Special issues that must be considered in order to complete a wind integration study are organised according to the elements of this flow chart. Figure i shows the main setup of the study, input data needed, links between simulations and changing main assumptions and analysing the results. This flow chart can also be used to guide integration studies about other variable generation sources, such as solar.

This Expert Group Report provides detailed recommendations for preparing wind integration studies on power system operation (scheduling and dispatch) and power system (resource) adequacy. Regarding load flow and dynamic/transient studies, this report presents the main points to consider when wind power is included in simulation analyses, instead of detailed recommendations on methodologies. This is because load flow and dynamic/transient studies are well established in engineering science with numerous text books giving adequate advice.

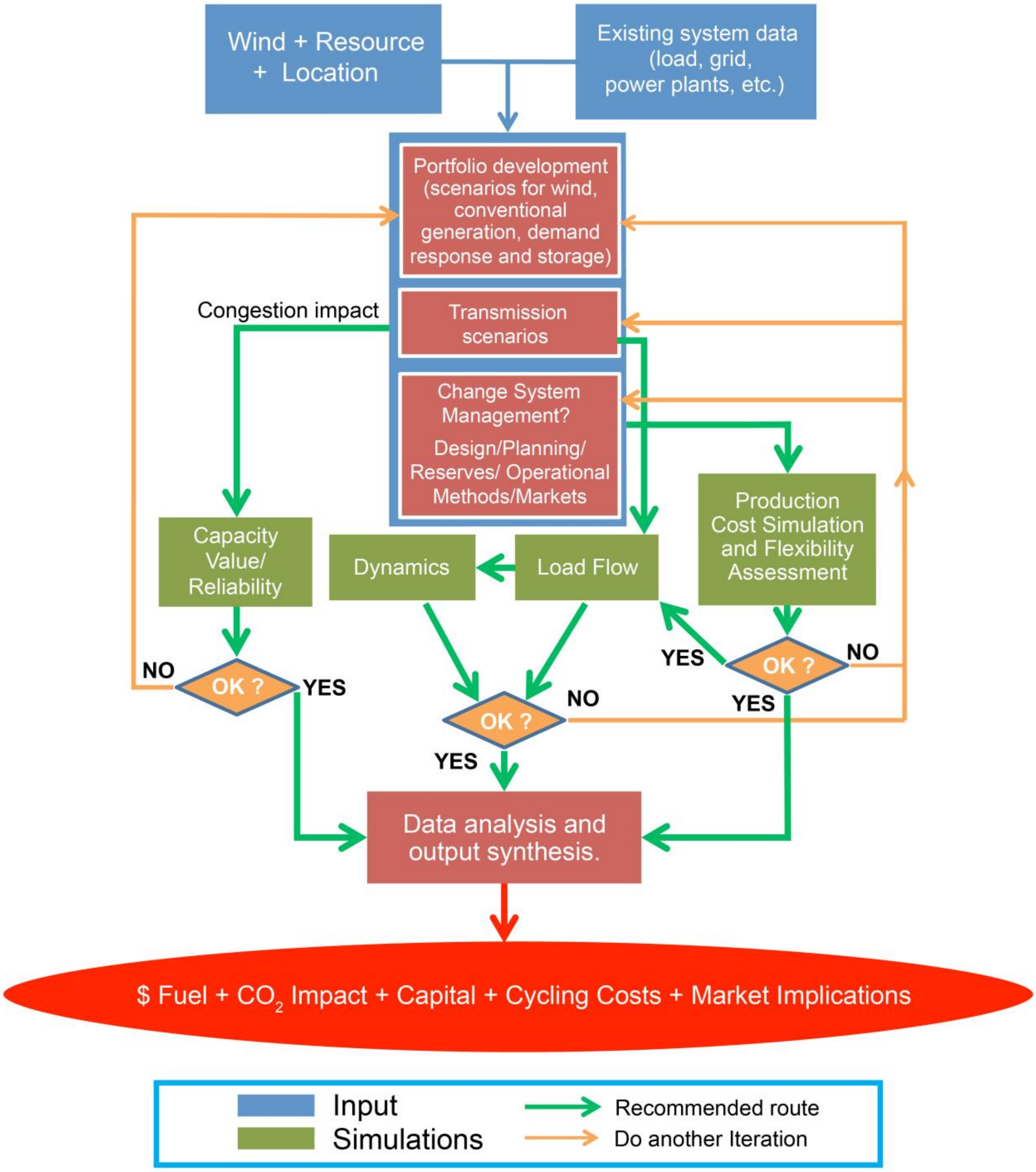


Figure i. Contents of a wind integration study

A full integration study is a complicated process, especially taking into account all possible iteration loops. Not all integration studies need to look at all aspects presented here. Transmission network adequacy and congestions are usually assessed first, in portfolio development, to feed as input to production cost simulations and capacity value (if area needs to be split to sub-areas). Iteration between grid simulations and production cost simulations are often needed. Capacity expansion model runs may be used in portfolio development, to produce generation portfolio scenarios. Or then foreseen changes for future system are made and the adequacy is checked in Capacity value/Reliability simulation.

A comprehensive wind integration study should clearly describe the many inputs and assumptions used and include the following:

- *Objective of the study:* what is included, and what is excluded
- *Existing power system data:* includes generation portfolio, power plant data, load data, transmission network, operational practice, power market structure, and wind plant size and location
- *Wind power related data:* detailed wind production data that correctly characterises plant performance and geographical spread, time-synchronised with load data, as well as data on wind and load uncertainty (forecast errors). Location of wind power plants for grid simulations.
- *Other assumptions that play a key role in results*: such as links to gas markets and heat demand (in cases with combined heat and power plants), demand response possibilities, other scenarios of (future) conventional generation and network characteristics as well as fuel prices, taxes, CO_2 allowances and emission limits.

Key tasks that comprise the integration study include the following.

- Data collection and quality checking
- Portfolio development: determining scenarios to be studied and base case for comparisons
- Impact of wind power on short term reserves as statistical data analysis
- Running capacity (resource) adequacy analysis to assess capacity value of wind power
- Running production cost simulations to see how wind power impacts the scheduling and dispatch of conventional generation, and operational costs of the system
- Running transmission network simulations to see that the transmission network is adequate
- Running iterations based on initial results if there is need to change the generation or transmission portfolio or operational practices
- Analysing the data and presenting the results

Depending on the penetration levels studied, some components of the study can be omitted. To start with, at lower penetration levels (below 5-10%[1]) portfolio development can just include the power system as it is operated today. The main simulation components are production cost simulation and load flow, in order to evaluate the impact of wind power to the other power plants as well as needs to upgrade transmission network. Also impacts to reserve requirements may be addressed. For higher penetration levels it will be more relevant to assess capacity value and dynamic stability and make a more detailed flexibility assessment. Even if capacity value of wind power is usually not critical at low penetration levels, it has often been included in the

---

[1] Penetration level is the percentage contribution of wind to yearly electrical energy (gross demand). How low penetration is defined will depend on power system characteristics: 5% is low in most systems, whereas 10% can be still low in some but already high in others. For example, depending on the load and wind resource, challenging high penetration level situations (with 50% or more from wind power at any single instant) can occur even when wind contributes less than 10% of yearly gross demand.

studies. And in many studies so far transmission network is not studied but simplified approach is taken with only production cost simulations. A full study is a complicated process especially taking into account all possible iteration loops.

Iteration of the study elements will often be necessary based on initial results at least when higher penetration levels are studied. For example, if reliability constraints are revealed in generation, transmission, or reserve margins, then iteration will be required to adjust the installed capacity of the remaining power plants (the portfolio), the transmission grid, and the operational methods of system management (like reserve allocation).

Assessing significant wind penetration levels usually requires conducting studies projecting 10–30 years in the future. Such simulation results can illustrate ways to prepare for possible impacts of adding wind. The results can show how changes to market structures and operating procedures could help ensure reliable and economic systems assuming high penetrations of variable power.

The Expert Group recommends the following procedures and considerations for conducting integration studies. Penetration level refers to energy penetration share of yearly generated wind power from yearly electricity consumption.

Portfolio Development

Generation and transmission scenarios

- When studying small amounts of wind power (penetration levels where wind share in energy < 5–10 %), wind power can be studied by adding wind to an existing, or foreseen system.
- For larger penetration levels, changes in the remaining system may be necessary, taking into account flexibility needs and additional network infrastructure. Since larger amounts of wind power, e.g. 30% energy share is further in the future, it is essential to have a realistic estimation of which other plants that are available at that time.

Operational methods

- When studying small amounts of wind power (penetration levels < 5%–10%), existing operational practice can be used as a starting point. For higher penetration levels, additional scenarios or operating practices should be studied.
- Market structures/design should be assessed to enable operational flexibility.

Reserve requirements/allocation method

- Data: Input data should include synchronous wind and load time series (at least hourly) and wind/load forecast error distributions. Generation outage distribution may also be used.
- Method: Level of risk should be chosen based on existing operating practice, for example to cover 95% of the variations in load and net load (load minus wind power) output.
- Calculations should be made for the appropriate time scales, corresponding to existing operational practice (like automatically responding in seconds-minutes, and manually activated in minutes-hour to several hours). Split the input data for these categories with care not to double-count sources of variability or uncertainty.
- Variability and uncertainty from wind and load (and generation) should be combined, keeping the same risk level before and after adding wind. Whatever statistical method is applied, it should take into account that variability and uncertainty of wind are not normally distributed.

- With increasing penetration levels dynamic reserves should be used rather than static reserves.

Capacity Value of Wind Power

Data

- The robustness of the calculations depends on the volume (years) of chronological synchronised wind and load data, that capture the correlation with wind and load data. Data on generation installed capacity and forced outage rates are also used in the calculations.

Methodology

- The preferred calculation method is a full effective load carrying capability (ELCC). Approximations should be avoided where possible.
- The preferred ELCC calculation includes the following:
  - Convolving generator capacity and forced outage to produce a capacity outage probability table (COPT) of the power system, which is a table of capacity levels and their associated probabilities
  - Loss of load expectation (LOLE) for each hourly demand level calculated from the COPT table, first without the presence of wind generation—wind is added as negative load, and load is increased until the same LOLE is reached as the one without wind power
- If there is insufficient data for ELCC then approximation methods can give useful insights; however, the limitations of such should be recognised.

Production Cost Simulations and Flexibility Assessment

Data

- Synchronous data for wind and electrical load is required with at least hourly resolution for at least 1 year, but multiple years are preferable. It is important to capture the smoothed-out variability of wind power production time series for the geographic diversity assumed. The study should use wind forecasting best practice for the uncertainty of wind power production assumed for the (future) year of study, with possibilities to update forecasts closer to delivery hour.
- Data for conventional power plants should include any possibilities or limitations of flexibility, like ramp rates and start-up times and costs. Synchronous data for run of the river hydro also becomes critical for hydro dominated systems.

Methodology

- System characteristics and response should be captured through operational simulations and modelling Unit Commitment and Economic Dispatch (UCED)
- The flexibility options should be modelled, as well as any constraints of flexibility. These include generation unit ramping and start/stop limitations and the associated costs, as well as hydrological constraints in the case of hydropower. The operational practices that may enable or limit flexibility should be taken into account.
- The possibilities of flexibility that exist in neighbouring regions should be incorporated. To accurately model the limitations of interconnections, the neighbouring system should be explicitly modelled, including also the wind power installed there. Alternative approaches include: assume full availability of interconnectors, or assume fixed flows obtained from other studies or based on market prices in neighbouring regions. These

approaches will err on the optimistic and pessimistic sides, respectively, and should be mentioned clearly in the study conclusions.

- To capture the limitations from the transmission network, it is important to consider congestion and N-1 security within UCED (the system should always operate in a state where any single largest failure, N-1, could happen without risking security). To reduce the computational burden for large systems or where stochastic optimisation is used, net transfer capacity, or iterative methods can be used. In systems with very high levels of renewable generation, it may be also necessary to model additional stability constraints arising from the studies described in Section 6.2 Dynamic Stability Analyses.
- Study results and conclusions are particularly sensitive to the non-wind case used as a basis for comparison and to the assumptions regarding the types of generation that wind power will displace. This is especially true when estimating integration costs. Just adding wind power, or using a scenario with equivalent wind energy but with a perfectly flat profile, may result in impacts not entirely related to wind energy. The use of generation planning models to ensure consistent scenarios should be considered.
- The existing flexibility should be assessed. Indicators of whether additional flexibility may be economic should be provided, together with the time scales of response times and other properties that the power plants must provide to efficiently integrate the level of wind energy projected. For higher wind penetration levels, understanding the cost of cycling on existing fossil plants and acknowledging and/or including new potential sources of flexibility, including fossil plant retrofits, is important.

Transmission Grid Simulations

Load flow simulations

- Validation of all input models is important (conventional generators, wind turbine, and load). Wind turbine models should be linked with evolving turbine technologies and grid code requirements, in order to simulate wind turbine capabilities in a relevant way for the system in question. Appropriate model complexity will be dependent on study application.
- Wind power studies will need a wider range of credible analysis cases, not just traditional min/max load scenarios. An evaluation of the statistical relevance of snapshots (several single points in time) would be beneficial.
- Deterministic steady-state security including load flow and short circuit analyses should be performed to identify transmission network bottlenecks (i.e., congestion), assess the system's ability to control the voltage profile, and determine short circuit current levels.If congestions are set by other limits than thermal stability, then dynamic stability analysis are required to set these.
- Network loading (i.e., congestion) should be assessed by determining network branch loadings for wind generation and load combinations, over a year, both for normal and contingency situations. Bottlenecks can be identified in a probabilistic manner, analysing the overload risk and the severity.

Dynamic stability simulations

- Stability challenges may be totally different for different systems (e.g., frequency stability, voltage stability, or transient stability issues), implying that specific system studies may be required.
- Transient stability analysis should include the effect of protection devices for both network and converter-interfaced generating equipment. (Boiler/steam turbine models are not required.) Any fast-acting reactive power response devices such as Flexible

Alternating Current Transmission Systems (FACTS), and/or synchronous compensators, requiring wind/conventional generators' response should be examined during and following disturbances, to see how potential issues could be mitigated.
- When studying voltage stability, the possibility of deploying reactive power control capabilities of wind turbines is an important assumption as may result in unaffected or enhanced voltage stability.
- In small-signal stability studies modelling automatic voltage regulators is required, including power system stabiliser settings for synchronous generation. Wind power may help damping oscillations.
- Frequency stability studies:
    - Reduced inertia at times of high non-synchronous penetration will alter system response for both faults and contingencies. If wind penetration levels studied will result in more than 50% penetration levels during some hours for the whole synchronous area, this effect should be studied, especially for small power systems.
    - Modelling inertia, droop, and governor control settings of all units (both individual unit responses and system response to faults or contingencies) is important. It is important to consider the fraction of generation participating in governor control and manoeuvrable capacity.
    - Wind turbines can provide synthetic inertial response, depending on their operating point, and this should be considered. Fast-acting load response or storage may also be included.
    - A reduced network representation may be sufficient.

Analysing and Presenting the Results

- If the results show unexpectedly high and costly impacts of wind power to the system, consider the iteration loops. Changing operational practices may prove cost effective, or generation or transmission scenarios may be inadequate.
- When extracting results for the impacts, select the cases to compare with care and report the methodology and possible caveats in the findings. Assessing integration costs is especially challenging.
- Present the results stating penetration level of wind, size and type of power system, and the main assumptions and limitations arising from these.
- It is essential to consider that not only wind power, but all system changes, cause system impact. This means that if the wind power alternative is compared with another alternative, then an integration study should also be performed for the other alternative.
-

The Future

Integration study methodologies continue to evolve and will benefit from the experiences of systems operating with large amounts of wind energy. Recommendations for the main steps and methodologies to conduct integration studies will be updated as part of continuing international collaboration under IEA Wind Task 25. Recommendations on how to operate power systems in future have a link to policy and market development. Work that may influence future recommendations includes the following:

- Development of flexibility metrics and tools that can be used to evaluate the flexibility needs of the power system, and ways to achieve that flexibility
- Development of simulation tools that take into account the uncertainty of wind power in different time scales, and combine network constraints with unit commitment (UC) and dispatch constraints

- Exploring ways to set up simulation cases to be able to extract impacts and system costs
- Increasing knowledge about stability issues with very high penetration cases. Future grids with more DC transmission.
- Exploring the implications of market design and/or regulatory processes for wind integration. It is not now well-known how markets should be designed to incentivise flexibility and generation resource adequacy in systems with high wind energy penetrations.
- Studying how large amounts of wind power impact different market elements so that market integration strategies or alternative market designs can be recommended.

List of Acronyms

AC: alternating current
AGC: automatic generation control
AIGS: All Island Grid Study
AVR: automatic voltage regulator
CAES: compressed air energy storage
CIGRE: Conseil International des Grands Réseaux Électriques
COPT: capacity outage probability table
DC: direct current
DLR: dynamic line rating
DR: demand response
DSM: demand side management
ELCC: effective load carrying capability
ENTSO-E: European Network of Transmission System Operators for Electricity
EWEA: European Wind Energy Association
EWITS: Eastern Wind Integration and Transmission Study
FACTS: flexible alternating current transmission systems
FOR: forced outage rates
FRT: fault-ride-through
GW: gigawatt
GWh: gigawatt-hour
HVDC: high-voltage direct current
IEA Wind: The International Energy Agency Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems
IEA: International Energy Agency
IEC: International Electrotechnical Commission
IEEE: Institute of Electrical and Electronics Engineers
ISO: Independent System Operator
kW: kilowatt
kWh: kilowatt-hour
LOLE: loss of load expectation
LOLP: loss of load probability
MW: megawatt
MWh: megawatt-hour
NERC: North American Electric Reliability Corporation
nRMSE: normalised root mean square error
NWP: numerical weather prediction
PDF: probability density function
TSO: Transmission System Operator
TYNDP: Ten-Year Network Development Plan
UC: unit commitment
UCED: unit commitment and economic dispatch
UK: United Kingdom
UWIG: Utility Wind Integration Group (now UVIG for variability generation integration)
VSC: voltage source converter
WWSIS: Western Wind and Solar Integration Study

Contents

List of Figures

List of Tables

1 Introduction: Contents of a Wind Integration Study

Hannele Holttinen; flow chart: Juha Kiviluoma, Michael Milligan, Mark O'Malley, Jonathan Ruddy, J. Charles Smith, Lennart Söder, Frans van Hulle

Wind power will introduce more variability and uncertainty into operating a power system due to the natural factors that generate wind and the inability to perfectly predict them. To meet this challenge, there will be a need for substantial flexibility in the power system. Flexibility can be described as the ability of the power system to respond to change in different time scales. How much extra flexibility is needed depends on three factors: 1) how much wind power there is (i.e., the share of consumption covered by wind power production), 2) how well the wind power production can be predicted, and 3) how much flexibility already exists in the specific power system in question. It is technically possible to integrate very large amounts of wind capacity in power systems. The feasibility of integrating wind power is demonstrated through case studies that analyse the impacts on power systems.

Recommendations for how to conduct wind integration studies will depend to some extent on the penetration level to be studied. As a metric for penetration level this recommendations report uses the share of wind electricity from annual electrical energy (i.e., gross demand). There is no standard practice regarding what share of wind power in electric energy is considered low or high penetration. How low penetration is defined depends on power system characteristics: 5% is considered a low penetration level in most systems, whereas for more flexible systems, 10% can be considered a high or low penetration level, depending on the system. High penetration levels generally refer to penetration levels exceeding 20% of gross demand.

This recommendations report begins by outlining the phases of a complete integration study, as illustrated in the flow chart in Figure 1. The Introduction includes a short overview on wind integration. Then Sections 2–7 describe activities related to the main boxes of the flow chart in Figure 1: input data, portfolio development and system management, capacity value, production cost simulations and flexibility assessment, transmission grid simulations, and finally analysing and interpreting results. Each section addresses issues that are relevant to wind integration with a checklist of recommendations. The report concludes with a summary of the recommendations and suggestions for future work.

1.1 Contents of a Wind Integration Study

Figure 1 provides a flow chart illustrating an overview of what a complete integration study should contain. Not all studies include all of the flow chart components and it may not be realistic for all integration studies to perform each step proposed. A full study is a complicated process, especially taking into account all possible iteration loops. The flow chart is also applicable to other variable renewables, such as photovoltaics.

Depending on the penetration levels studied, some components of the flow chart can be omitted. To start with, at lower penetration levels (below 5–10% of energy), portfolio development can just include the power system as it is operated today. The main simulation components in this case are production cost simulation and load flow. This will estimate the impact of wind power on the other power plants and needs to upgrade transmission network. Impacts to reserve requirements may also be addressed. For higher penetration levels, capacity value and dynamic stability is often studied, and a more detailed flexibility assessment is useful. Portfolio development will also need to be addressed more in detail for higher penetration levels.

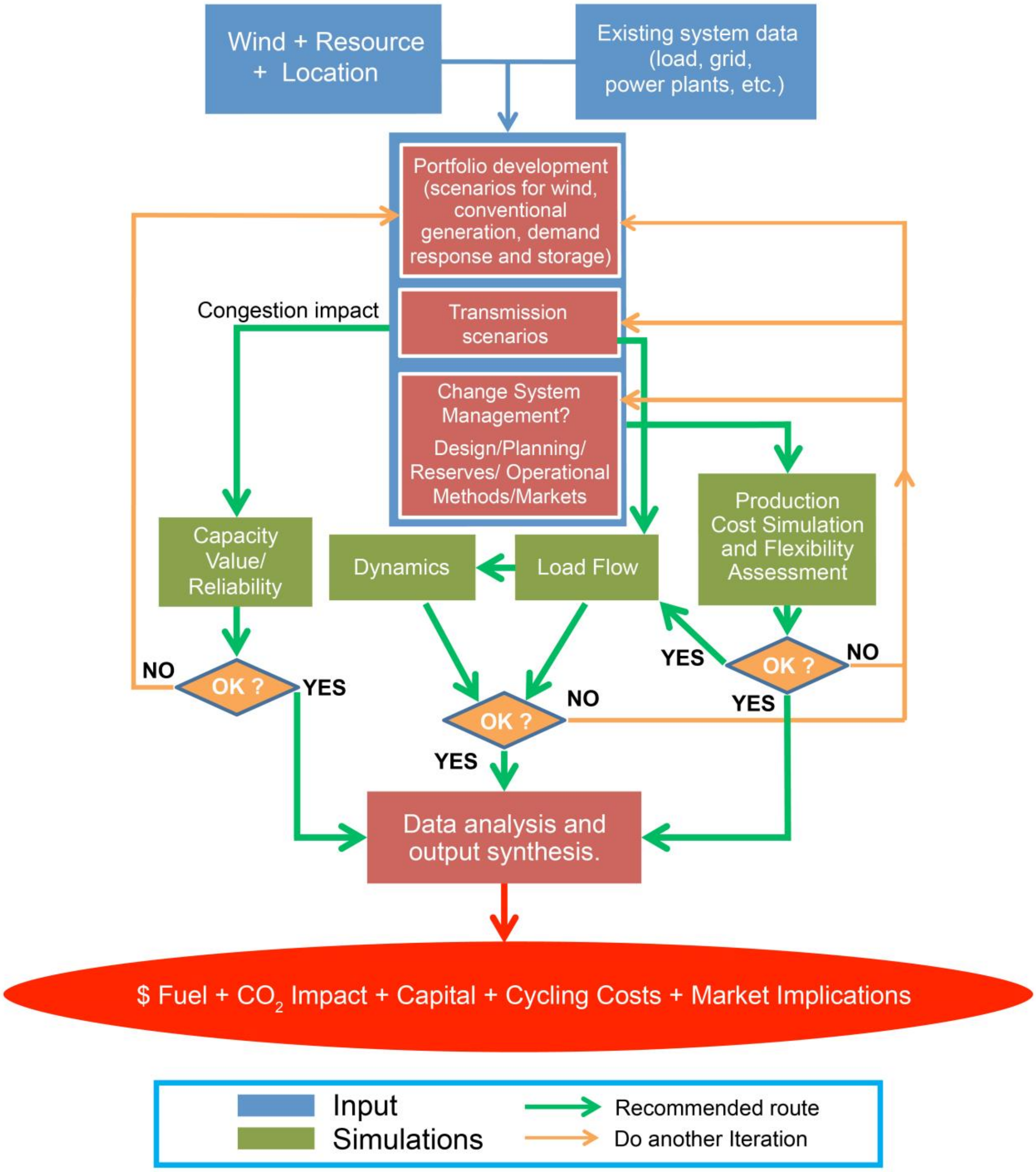


Figure 1. Wind integration study components. Flow chart showing a recommended route with iteration loops and possible routes when not all components are studied.

A wind integration study usually begins with a set of input data characterising wind power and the underlying power system along with a wind power penetration level that is of interest (the top two blue boxes in Figure 1). The electrical footprint must be chosen, which may include a subset of, or the entire synchronous system. Analysis of an entire synchronous system can characterise the full set of interactions that govern power systems. However, because studying the entire system can greatly increase the complexity of the study and may not be relevant for the phenomena of interest, a part of the system is often studied, with careful modelling of interactions between the boundaries of the study area and the remaining synchronous system.

Portfolio development needs to establish the kind of system that is studied, such as current or future system, the assumed generation fleet, and demand and flexibility options. The basic set-up assumptions will have a crucial impact on the results of the study. An important aspect is how wind power is added to the system—whether by replacing existing generation, adding wind power to the existing system, or developing optimised portfolios for both scenarios. Changes in system management may need to be made from the start to accommodate large amounts of wind power. This involves checking the options for flexibility available in the power system through operational measures and through the transmission scenarios studied. Allocation, procurement, and the use of reserves in a cost-effective manner may also have to be changed.

Wind integration studies usually involve investigations of transmission grid, simulations of the operation of power plants in the system, and calculations of the capacity needed to meet resource adequacy requirements in the peak load situations (represented by the green simulation boxes in Figure 1). Grid simulations (i.e., load flow and dynamic stability) involve contingency analysis and stability studies. More detailed stability simulations and flexibility assessment are necessary when studying higher penetration levels of wind power.

Reliability constraints from transmission or capacity adequacy or reserve margins will require iteration on the initial results to adjust the installed capacity of the remaining power plants (i.e., the portfolio), the transmission grid, and the operational methods of system management (such as reserves).

Analysing and interpreting results of wind integration studies may be challenging because the impacts of variable resource integration and the best options to remedy impacts can be difficult to determine and may be system-specific. Usually the studies try to quantify wind impacts by comparing simulation results from no (or little) wind with future higher amounts of wind power. Some studies try to estimate integration costs for the system. The benefits of wind power to the system can also be quantified, and they should be larger to justify/underpin the wind energy targets. Significant wind/solar penetration levels usually necessitate conducting studies that project 10–30 years in the future. Details on how to prepare for possible impacts of wind power on the system can also be extracted from simulation results. These results can help determine when to allow changes to market structures and operating procedures in order to help ensure reliable and economic systems once high variable penetrations power are realised.

1.2 Overview of Wind Integration Issues

All new power plants will need to be integrated in the power system by assessing the grid adequacy in longer time scales and implications to system balancing and dynamic stability in shorter time scales. Implementing wind power has impacts on power system management, economics, and efficiency. To keep the operational security and reliability at an acceptable level, some measures may need to be taken.

The studies often address different impacts, with different time scale resolution, and therefore different models (and data) are used. In this recommendations report and in Task 25 work, more system-related issues are addressed, as opposed to local issues of grid connection like power quality (see Figure 2).

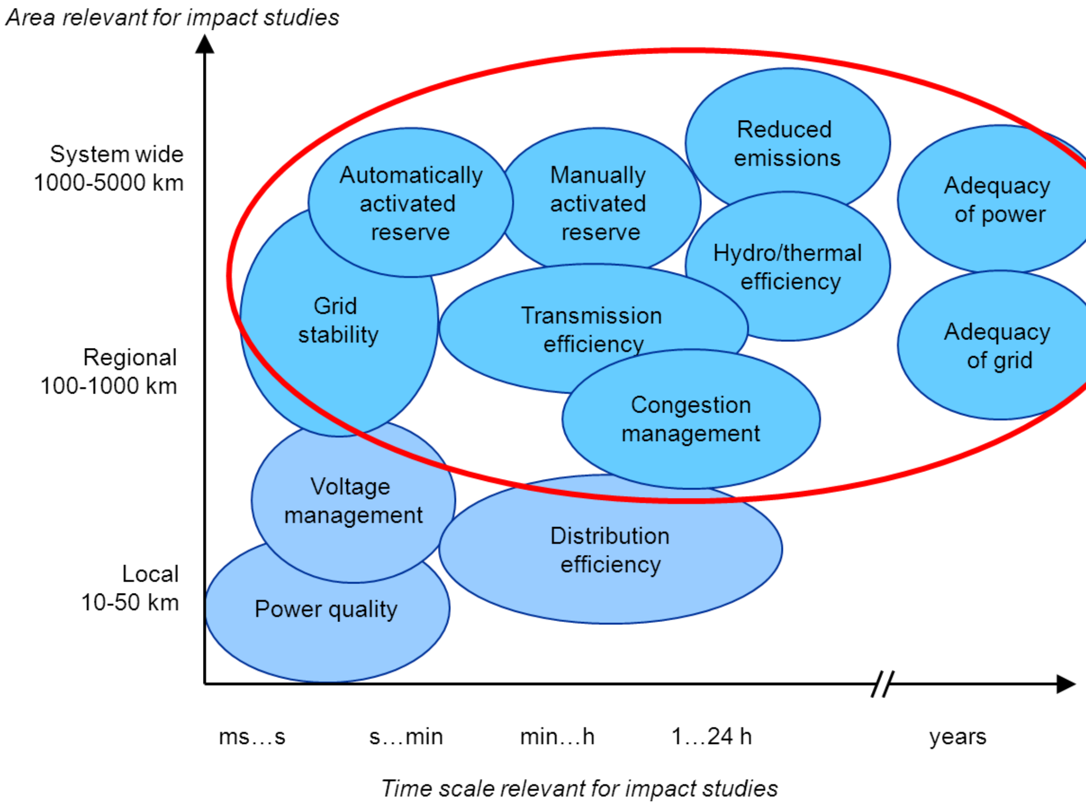


Figure 2. Impacts of wind power on power systems, divided in different time scales and geographic width of area relevant for the studies. The red line encircles those more regional scale issues that Task 25 has concentrated on. Operating reserve is divided into two categories: automatically activated reserves in seconds (frequency activated, primary/secondary reserve, regulation) and manually activated reserve in 5–15 minutes (minute reserve, load following reserve). Transmission and distribution efficiency refers to grid losses.

Power systems worldwide are quite different in regard to the operational characteristics of the installed generation plants, the inherent variability of system load, the rules and strategies practiced in relation to transmission capacity, the treatment of imbalances, and the network topology (well-meshed versus radial grids). Physical flexibility (i.e., existing generation capabilities), and administrative flexibility (i.e., market structure) both affect the ability to balance increased variability and uncertainty from wind power. The flexibility created by market configuration and conditions, including geographical extent and response of market operation, is quite different from country to country. Market design also affects the efficiency and adequacy of power and transmission.

Some impacts can only been seen in the medium-to-high wind power penetration (i.e., more than 5–10% of gross demand, annual electrical energy supplied by wind power). When wind penetration exceeds 10%, there are usually already several occasions during the year when wind provides more than 50% of load during 1 hour.

1.2.1 Balancing: Short-Term Reserves, Dispatch, Scheduling/Unit Commitment

Short-term operating reserves (time-scale: seconds to 1 hour): This issue is about how the uncertainties due to variability and forecast errors introduced by wind power will affect the allocation and use of operating reserves in the system. Power systems balance the whole system net imbalances. This means that uncertainties of wind power distributed to a large, system-wide area will be combined with other uncertainties the power system experiences, like those associated with load. General conclusions on the increase in balancing requirements will depend on region size relevant for balancing, initial load variations, and wind variability (the smoothing effect depends on how concentrated or well distributed wind power is sited).

Efficiency and unit commitment (UC) (time scale: hours to days): Here the issue is how the conventional capacity is run and how the variations and prediction errors of wind power change the scheduling of power plants: both the time of operation and the way the units are operated (ramp rates, partial operation, starts/stops). Critical situations like high wind and minimum load need to be addressed. Analysing and developing methods of incorporating wind power into existing planning tools is important to correctly take into account wind power uncertainties and existing constraints and flexibilities in the system. The simulation results give insight into the technical impacts of wind power, and also the (technical) costs involved.

1.2.2 Capacity Value and Adequacy of Power Generation

Capacity value and adequacy of power generation (time scale: several years): Here the issue is about total supply available during peak load situations. System adequacy is associated with static/steady state conditions of the system. The estimation of the required generation capacity needs includes the system load demand and outage rates of production units. The criteria used for the adequacy evaluation include the loss of load probability (LOLP) and effective load carrying capability (ELCC). The proper assessment of wind power's aggregate capacity credit in the relevant peak load situations must take into account the effect of geographical dispersion and interconnection.

1.2.3 Transmission and Stability

Transmission adequacy and efficiency (time scale: hours to years): The impacts of wind power on transmission depend on the location of wind power plants relative to the load and the correlation between wind power production and load consumption. Wind power affects the power flow in the network. It may change the power flow direction, or reduce or increase power losses and bottleneck situations. There are a variety of means to maximise the use of existing transmission lines like dynamic line rating (use of online information: temperature, loads), Flexible Alternating Current Transmission Systems (FACTS), and wind power plant output control. However, grid reinforcement is often necessary to maintain transmission adequacy when adding significant levels of wind capacity. When determining the reinforcement needs of the grid, both steady-state load flow and dynamic system stability analysis are needed.

System stability (time scale: seconds): Assessing the impacts of wind generation on power system dynamics will be important at higher penetration levels. The grid code requirements and control capabilities of wind power plants should be recognised within any study. The possibilities to support the system in normal and system fault situations include voltage and power control and fault ride through capability. The siting of wind power plants relative to load centres will have some influence on this issue as well. System stability studies with different wind turbine technologies are needed in order to test and develop advanced control strategies and possible use of new components (e.g., FACTS) at wind plants or nearby busbars.

1.2.4 Enablers of Wind Integration

Increased variability and uncertainty due to wind power can increase the need for flexibility in power systems. Flexibility means the ability to adjust generation output level or demand up or down to regulate the system in response to changes. Today this flexibility is mostly managed with conventional power plants. Operational measures can both increase flexibility options and decrease needs for flexibility—for example, by enabling transmission possibilities in larger balancing areas and introducing new market mechanisms to enable full use of existing flexibility in generation units. Demand response can offer cost-effective flexibility. New flexibility can be added as flexible power plants, transmission lines, and storage capacity. When flexible conventional power plants reduce output, they save the fuel for later use. Wind turbines can also be used to provide flexibility; however, reducing the possible output level of turbines to provide regulation involves loss of energy. This means that it is one of the most expensive ways to provide flexibility and should only be used when other more cost effective options are not available. Figure 3 shows a general view of flexibility options and their relative cost effectiveness. Smart Grids can enable the use of demand side management (DSM) and distributed generation flexibility.

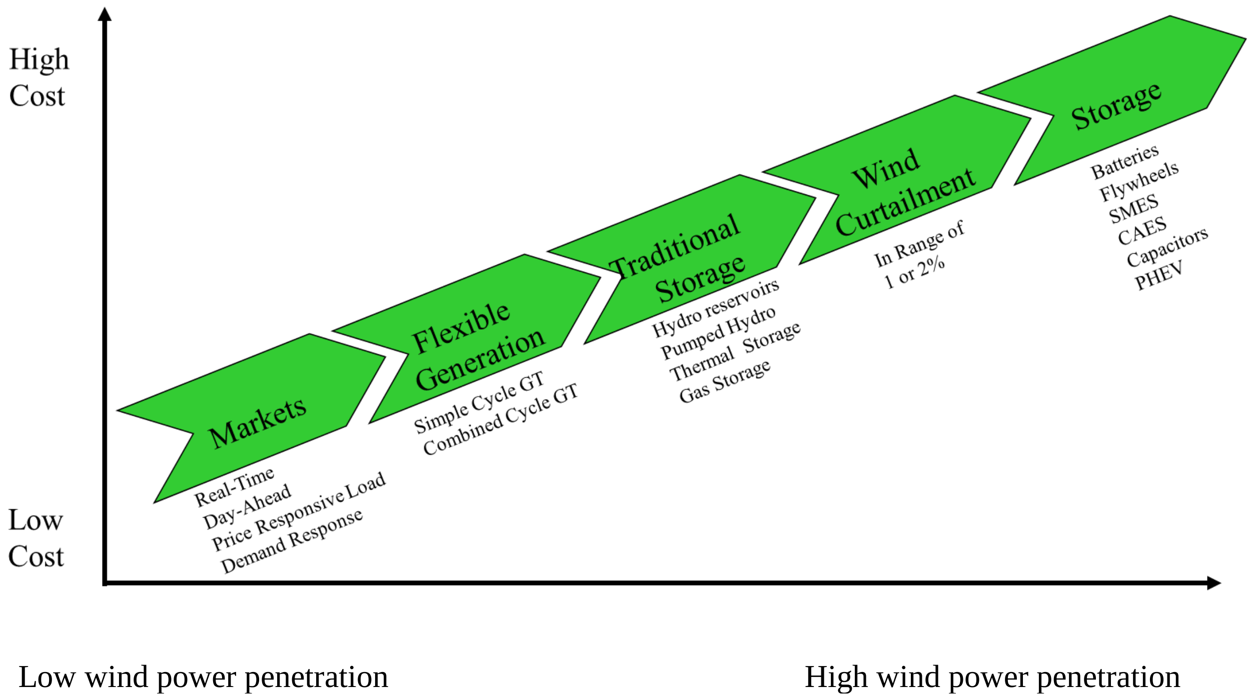


Figure 3. Cost of increased flexibility in power systems, general trend (Original source: UWIG)

2 Input Data

This chapter describes the first blue input boxes in the wind integration study components flow chart.

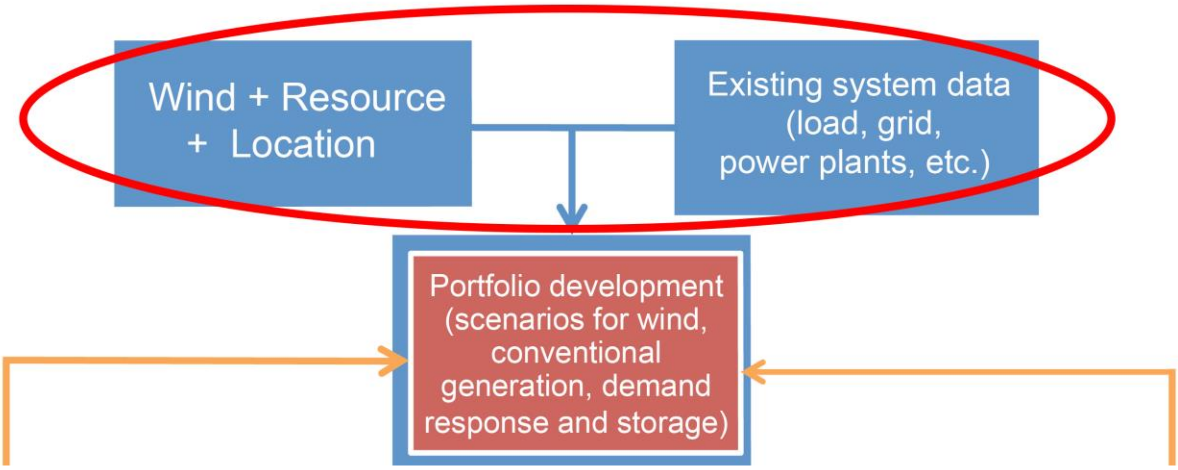


Figure 4. Wind integration study components: inputs needed for a wind integration study.

Wind integration studies need data on wind power, load, other generation, and the transmission grid. When the integration study is aimed at estimating the potential impacts of large amounts of wind power in a future year, the assumptions regarding all of these data will impact the results considerably.

Different volumes of data will be needed in different simulation parts. The transmission grid is often modelled only as net transfer capacities between balancing areas when optimising unit commitment and dispatch, whereas the complete time series of wind and load are replaced by snapshots in grid simulations where the transmission grid is modelled in detail.

2.1 Wind Data

2.1.1 Data Requirements

Bernhard Lange, Hannele Holttinen, Michael Milligan

Representative data for future wind power production time series of a certain length and in a certain temporal and spatial resolution is needed for any wind integration study. If balancing is included in the study, wind power forecasting time series are also needed. Data for wind power production should capture the variability and uncertainty, from the system area simulated, and for the future anticipated wind power plants. The detail of the data as well as the important characteristics to be considered will vary according to the simulation (Table 2).

<u>Wind input data for capacity value / power adequacy calculations</u>: Capacity value calculations capture the contribution of the wind plant to resource adequacy. The result for this calculation is dominated by the generation available during the highest load hours, which are a small part of the complete time series. Because the relationship between wind and load is a key factor, synchronous time series are crucial. If synchronous time series are not used, then the model inputs may represent a stormy day with high levels of wind power in the wind data, while representing a hot, still day in the load data. This is clearly inconsistent. If other renewable power generators, such as photovoltaic generation, are also considered in the study, time synchronisation between these is also necessary. To obtain a sound statistical basis of high-

load/low-wind cases, multiple years are needed. The length of the period of investigation required is dependent on the size of the system, the load curve, and the penetration of wind power on the system. A temporal resolution of 1 hour is usually adequate for this type of study, because variability of wind generation in time scales below 1 hour does not impact the results. For the case of Ireland, 7 years investigation length and hourly resolution has been deemed sufficient (Hasche et al. 2011).

Wind input data for unit commitment and dispatch (UCED) simulations, including reserve requirements: UCED is done in advance, planning the generation levels to best match the varying load. The simulation therefore requires the use of wind power forecast time series in addition to the actual generation time series. The same applies for the impact of wind power on reserve requirements, because this is a result of the forecast error. The required temporal resolution depends on the model. The minimum requirement to catch wind power variability is using chronological, hourly wind plant generation data. However, 10–15 minute data will capture more wind power impacts. It is important to have enough power generation measurements from wind power plant sites to cover the dispatch area. For an UCED simulation, the wind generation and wind generation forecast time series have to be synchronous with load data. One year of data may be enough for some studies, but other studies may aim to quantify year-to-year differences, therefore needing several years of data. There is some evidence that higher wind years have somewhat higher variability, but the differences are not very large (Holttinen et al. 2011). It is thus recommended to include data from a windy year to make sure the variability of wind is not underestimated.

For the reserve requirement, the probability of the largest forecast errors is the determining factor. As these “tails” of the probability density function (PDF) differ from year to year, it is better if the PDF is derived from a time series of many years to have better accuracy (Dobschinski et al. 2010). If only the wind-induced reserve requirements are calculated and no UCED simulation is performed, only the PDF of the forecast errors is needed, rather than the complete time series. This can be combined with other contributions to the reserve requirements (i.e., PDFs for load forecast errors and power plant outages).

Usually the variability in seconds (up to a minute) time scale is independent for each wind turbine, and will cancel out almost completely in a balancing area. If the very short time scale, automatic reserve requirements need to be studied, second/minute variability needs to be separated from 10–60 minute variability. One such method is described in King et al. (2012).

The characteristics for the time series data needed for capacity value and UC studies are summarised in Table 1.

Table 1. Requirements for time series input data of wind power generation for integration studies.

	Capacity Value / Power (resource) Adequacy	Unit Commitment and Economic Dispatch (UCED) Including Reserve Requirements
Temporal Resolution	Typically hourly data are enough, unless dispatch is faster, or wind variability below 1 hour is important	Dependent on the resolution of the dispatch, typically 5 minutes to 1 hour
Spatial Resolution	System-wide time series. It is more important to catch the levels of wind output during peak load situations than to incorporate smoothing effect of variability.	System-wide time series, incorporating smoothing effects
Length of Investigation Period	Long time series of typically 6–10 years	UCED: One year of data is usually enough, but more years are better, especially include high-wind year to capture possible variability; for reserve requirements longer time series improve the assessment.
Data Synchronisation	Synchronous wind and load time series, if applicable, also synchronous time series of other weather-dependent generation	Synchronous wind and load time series, if applicable, also synchronous time series of other weather-dependent generation
Wind Power Forecast Time Series	Not required	Forecast time series with the same characteristics as above; for reserve requirements, several years of data to capture extreme events

Wind input data for load flow analysis: For load flow analysis, the spatial distribution of the wind generation is of high importance, in addition to the magnitude. The spatial distribution should be that of the grid under investigation (i.e., the nodes of a transmission grid). It is crucial to choose a realistic future distribution of turbines connected to these nodes. If the turbines are connected via a meshed grid, their generation has to be distributed between different nodes (Wolff et al. 2007).

Since load flow calculations are rather time-consuming, usually snapshots (several single points in time) are considered and no time series simulation is performed (e.g., as hourly mean generation values).

For load flow analysis, spatially resolved information of the load, all generation plants and the grid is needed. To investigate extreme load flows, the information should ideally be the extreme cases of a very long time series, from wind/load/other generation worst case combination. Since acquiring such data may not be possible, different extreme situations of wind power generation, other generation, and load are often combined. They are from different points in time, but are chosen such that they could realistically occur simultaneously. For the quantification of the probability of extreme load events, the frequency of occurrence is necessary for the situations used.

Wind input data for system stability studies: Wind integration studies of system stability focus on the electrical behaviour of wind power plants in interaction with the grid. Simulation tools for electrical systems are used for these investigations. For these, realistic models emulating state-of-the-art wind turbines and wind farms are needed. The impact from centralised wind farm controllers on the operational behaviour should be captured. Although desirable, time series calculations are rarely performed and mostly the wind input is kept constant for each calculation's case (See Section 2.1.4).

2.1.2 Wind Generation Data

Hannele Holttinen, Michael Milligan, Bernhard Lange, Nickie Menemenlis

Analysis of actual wind plants has shown that the variability of wind power output declines on a per-unit basis as the level of installed wind capacity increases. This is because the wind at one location is only partially correlated with nearby turbines or wind plants. Correlation is generally smallest at the shortest time scales, increasing somewhat at longer time intervals. Representative wind plant data for an integration study should incorporate the variability and smoothing impact of the system area with anticipated, dispersed wind sites because wind power variability and uncertainty are key drivers of the study results. Siting of the turbines in the most realistic manner is also important for the transmission studies to model how they are located relative to consumption centres.

General information about the smoothing effect of large-scale wind power exists:

- Per-unit variability of wind generation decreases when there are more wind power plants distributed over the area.
- Per-unit variability of wind generation decreases as the time scale decreases—the second and minute variability of large-scale wind power is generally small, whereas the variability over several hours can be large even for distributed wind power.
- The size of the area and the way wind power plants are distributed is crucial: larger areas decrease the number of hours of zero output—one wind power plant can have zero output for more than 1 000 hours during a year, whereas the output of aggregated wind power in a very large area is always above zero.
- Geographic characteristics of the wind plant location and surrounding area can have a significant influence on the wind plant variability and uncertainty. For example, offshore wind plants are typically more geographically concentrated, and the offshore wind resource has been found to be generally more coherent, thus increasing the per-unit variability compared to onshore wind power.

Ideally, one would have actual high-resolution wind production data from all sites included in the study, and those would be input to the integration study. In general, data can be obtained from measurements and model data. Using existing wind power plant production data will clearly provide realistic smoothing characteristics. However, for capturing sites that are outside the data, and new higher turbines, or larger share of offshore wind, this approach has caveats. Using model data for wind can capture larger areas and better mimic future scenarios of sites, but may have caveats in representing the overall wind power production of the area correctly. Model data for wind is improving; however, real wind power production data from several sites still shows more smoothing effect than model data has shown (Holttinen et al. 2011).

If measured power production data is used, the wind energy penetration level is often lower than that to be studied. Simple up-scaling of data from existing wind plants to represent an increased level of wind capacity is an incorrect procedure, and will result in higher per unit variability than would be the case in reality. If the data already contain enough sites and number of turbines to reach the smoothing effect possible from the area in question, then up-scaling will produce realistic time series. A smoothing effect can be incorporated in a time series by sliding averages of the data, filtering out some of the fast variability. Although advanced statistical techniques could in principle be applied to this problem, there are not likely sufficient data to support this type of study because the wind plant behaviour depends on local weather, topography, and other factors. To further complicate the issue, the studies often evaluate the integration of potential future wind power plants that do not exist today. Various approximation methods exist to estimate the wind power production for future wind plant locations. It is important to cover an area as large as anticipated and have dispersed data that incorporates the smoothing effect in variability.

If the wind data needed for grid integration studies cannot be derived from actual measurements, it is recommended to use simulated data based on numerical weather prediction (NWP) models. However, measurements still play a crucial role in validating and improving the models and determining parameters used in the simulations.

In these simulations, wind speed on small geographic grids (such as a 2-kilometer square) are extracted at wind turbine hub height and at locations that represent potential future wind plant development. To represent large wind plants, the simulated wind power output from appropriate geographic grid cell locations are combined.

Data is usually needed on an hourly basis. If sub-hourly data are needed, it is common to capture the short-term variability characteristics from actual, operating wind power plants and apply that to future hypothesised wind plants.

When using model data, it is recommended to check the variability of the data by comparing it with measured large-scale wind power production data. The simulation should be setup to model the known production data, such that the model results can be compared with the measurements. Care must be taken so that the smoothing effect is modelled correctly. The standard deviation of the time series of variations is one option to check this, as seen in Figure 5 for hourly variation and in Figure 6 for 10-minute variations.

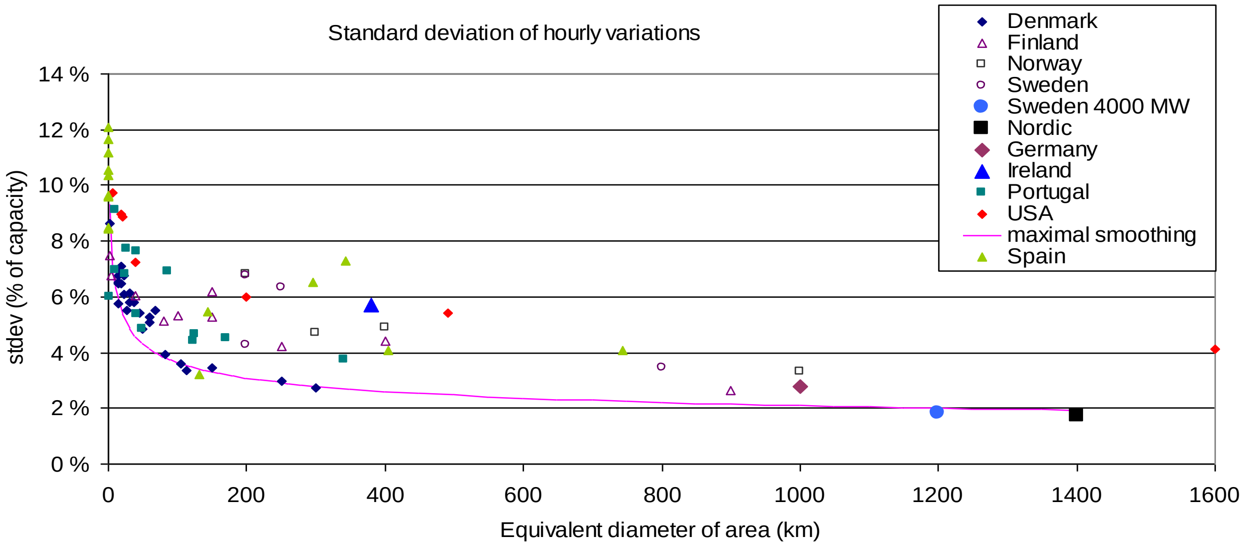


Figure 5. Indication of smoothing effect in the data, from standard deviation of the time series of hourly variations of wind power production. The size of the area is estimated as equivalent to the diameter if the area were a circle. (Source: Holttinen et al. 2009)

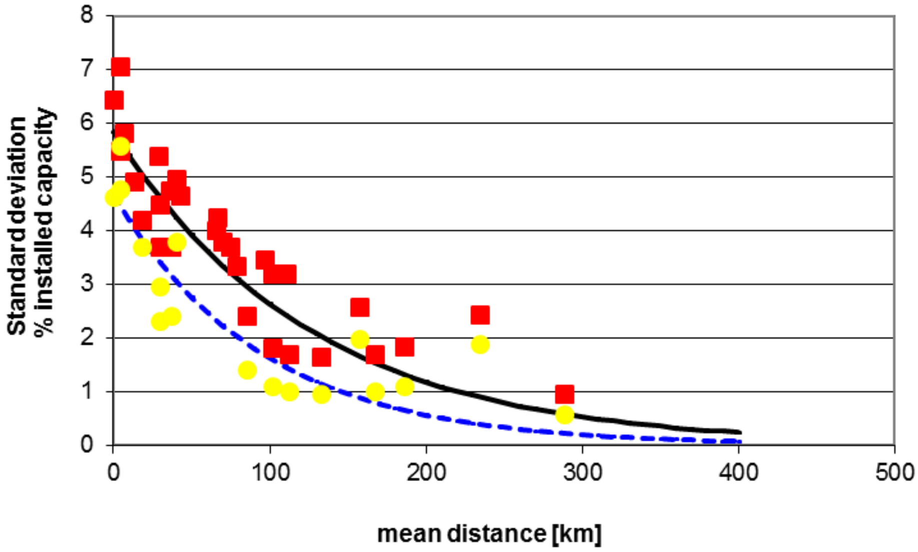


Figure 6. Standard deviation in percent of installed capacity for 10-minute (circles), 30-minute (boxes), 10-minute-fitted (dashed), and 30-minute-fitted (straight line) change of total wind power as a function of mean distance between all wind power stations (Söder et al. 2012). Mean distance is calculated from a representative rectangle covering the area of the wind power plants.

2.1.3 Wind Forecast Data

Hannele Holttinen and Bernhard Lange

Forecast errors for wind power are relevant for balancing studies—UCED and reserve requirements—but are not needed for capacity value or grid studies. For wind power, it is important to take into account the improvement in the forecast accuracy at shorter forecasting intervals of 6 hours ahead and shorter (Figure 7).

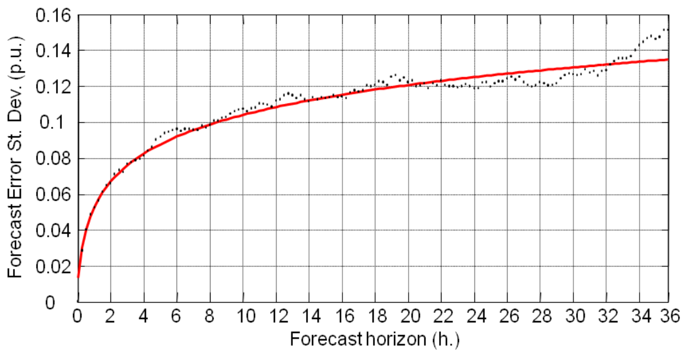


Figure 7. Normalised standard deviation of wind power forecast error for 12 GW of installed capacity versus forecast horizon (Source: Gibescu et al. 2009). Solid line is a curve fitting.

In addition to the forecast horizon, the forecast error depends on many other influences:

- For local forecasts, the error depends on local conditions, the size and location of the wind farm, and geographical spread.

- For regional forecasts, the error depends on the number of wind farms, their size, and spatial distribution.
- The error depends on the weather prediction model used as input.
- The error depends on the amount and quality of the measured data used as input to the system.

The average root mean square error normalised (nRMSE) to installed capacity for a 3-hour forecast for single wind farms of 4.5–300 MW (nominal power) in Germany is 8.5%. For the whole German wind power generation (3 908 MW mean generation), the nRMSE of a 3-hour forecast is approximately 3.1%.

As forecast accuracy is steadily improving (see for example Garcia Casado, 2013), existing forecast data will overestimate future uncertainty of wind power. Thus assessment of future impacts due to wind means simulating the forecast errors to get the uncertainty due to wind power. These errors depend on the quality of the prediction system and the analysed forecast horizon, which also illustrates the importance of reducing large forecast errors by optimising wind power forecast tools. Forecast error reduction needs to be estimated to the extent realistic in future wind generation scenarios.

For estimating reserve requirements, data periods having extreme rare forecast error cases are important. Forecast errors are not normally distributed, and have more extreme errors than a normal distribution (see Figure 8). Characterising the rare events for wind power would require several years of data to obtain results with adequate statistical reliability. When using short-term forecasts with horizons of 2–3 hours, the dependency on the past data set is probably not as critical because the situations can be seen better from shorter forecasts, reducing the largest errors. For the operational domain (short-term reliability assessment), wind power and load uncertainties need to be provided by a probabilistic forecasting system, which allows a dynamic characterisation of the uncertainties.

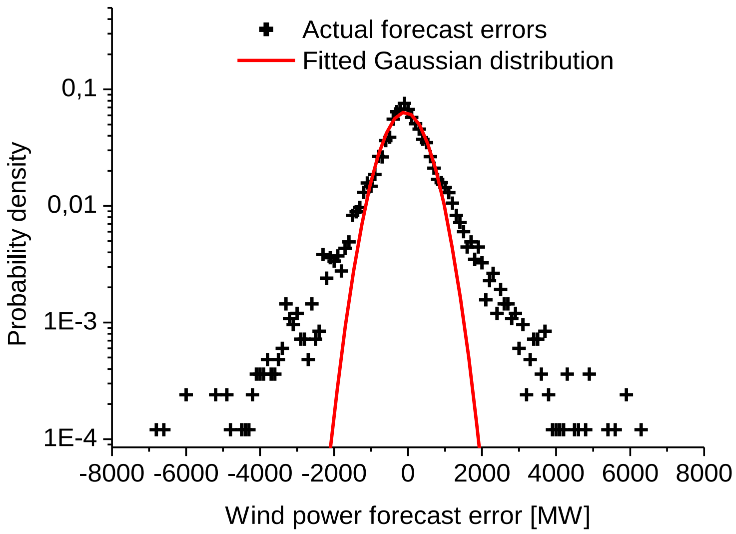


Figure 8. Larger forecast errors are more probable than a normal distribution would estimate. (Source: Lange et al. 2006)

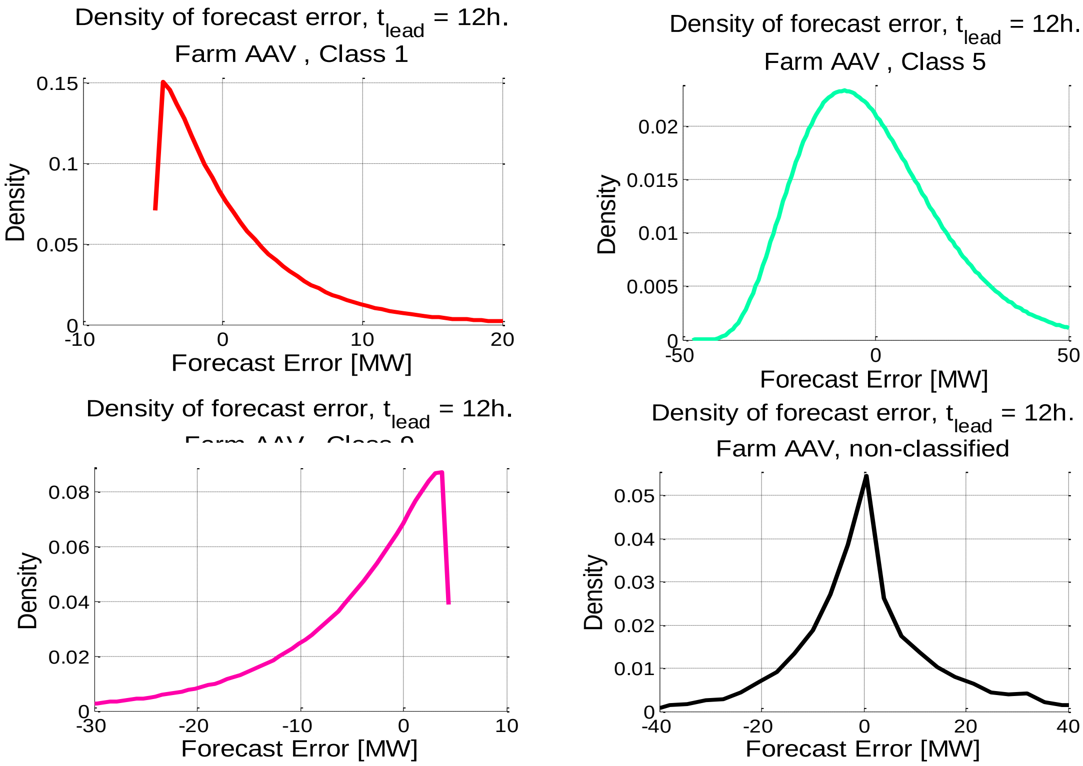


Figure 9. Forecast error distributions for different generation levels (top left for low forecasted generation, top right for medium generation level and bottom left for high generation). The bottom right graph corresponds to the case with all the data (no classification with respect to the generation level) (Menemenlis, Huneault, Robitaille, and Holttinen 2012).

For UCED studies, a time series of the forecast error along with the generation data are needed. If these cannot be taken from forecasts performed in the past, a dedicated forecast system has to be set up and used to produce the forecasts for the data set needed. If this is not possible, simulated forecast error data have to be used. This is usually done by describing the error distributions for different situations (e.g., by time of day and period of the year or for specific meteorological conditions). The distributions describing forecast errors, taking into account that large errors are more frequent than in normal distribution, are band-limited and have fat tails capturing the rare events (Figure 8). Moreover, they depend on wind generation level (Figure 9). Efforts have been made in estimating the correlation between wind farm generation forecast errors (Giebel et al. 2007) and a methodology for their aggregation has been summarised in Menemenlis, Huneault, and Robitaille (2012). However, it has to be noted that simulated forecast error time series will not capture the complete characteristics of the weather-dependent variability together with their spatial and temporal correlations.

2.1.4 Wind Turbine Capabilities

Frans van Hulle and John Olav Tande

System integration studies need to take into account the relevant control features that enable wind turbines and wind farms to provide services according to the power system needs for voltage stability, frequency stability, and system restoration. These control features are part of specific wind turbine technology characteristics, and thus have to be regarded as input data for system studies. Specific control performance and related parameter values are prescribed by the local network operator in so-called grid codes (in the United States, these are named interconnection regulations). The relevant capabilities to take into account are as follows:

- For system dynamics analysis:
    - Fault Ride Through
    - Active Power Frequency Response
    - Inertial Response
    - Reactive Power

- For steady state analysis:
    - Active Power
    - Reactive Power

A brief description of these wind plant control features is given in this section. Later on, Section 6.1 and 6.2 discuss some aspects related to modelling these control features at the wind plant level and the aggregated level (relevant for system studies), mainly for dynamic stability analysis.

Models for various classes of wind turbines and wind power plants are being developed, and although much progress has been made, generic wind models require further development (IEC 2012). Depending on the nature of the analysis, the wind models should incorporate the underlying electrical machine and power electronic/control system dynamics, supported by the grid code requirements (e.g., droop characteristics, imposition of ramping limits, over/under frequency response, volt/var controls, and emulated inertial response). The wind turbine capabilities may be included as a study variant. A series of reference models for wind generators is illustrated in Chapter 6 of CIGRE TB 312 (CIGRE 2007) namely related to:

- Induction generator without power electronics
- Induction wind turbine generator with dynamic slip control
- Doubly-fed induction wind turbine generator
- Synchronous or induction generator connected through a back-to-back converter.

Different levels of dynamic models can be considered according to the dynamic phenomenon under investigation—they are, in order of accuracy:

- Detailed models of a specific machine and controls provided by the manufacturer
- Generic models according to the technology with standard parameters which may be enriched by specific controls and parameters
- Simplified equivalent models of the whole wind farms

<u>Active power (for steady state studies and UCED, power flow analysis, etc.)</u>: Active power is representing all possible control functions, enabling the active power output to display specific behaviour (ramping up and down, delta, etc.). This control represents the capability of wind plants for providing reserve and balancing services (primary, secondary, tertiary reserve). The capability of active control of the electrical power output should be regarded in combination with wind (power) forecasting and on-line monitoring.

<u>Reactive power (for steady state and dynamic stability studies)</u>: Reactive power capability represents the control features enabling wind turbines and wind farms to provide reactive power to assist in maintaining voltage stability in the network, more or less independent of their actual active power production. Reactive power capability is defined both at maximum (rated) active power and below rated power.

<u>Fault Ride Through (dynamic stability studies)</u>: Fault-ride-through (FRT) is the capability of wind power plants to stay connected when (severe) voltage drops occur in the network as a

consequence of (secured) network faults and to continue stable operation during and after the network fault, while respecting minimum voltage levels and time limits specified in so-called FRT profiles. It includes after fault-clearance, respecting minimum voltage and time criteria (specified in so-called FRT profiles) in providing control actions. In order to support the network voltage and frequency stability, FRT includes the provision of fast reactive current injection by the wind power plant as well as post-fault active power recovery capability. FRT is specified with help from FRT profiles (voltage against time; Figure 10). Figure 10 indicates the retained voltage level, *Uret*; the voltage, *Uclear*, at fault-clearance time, *tclear;* and the recovery voltage level at *t* recovery (EWEA 2012). The sloped line in the FRT profile neither represents physical wind turbine behaviour nor grid voltage-time behaviour (which in practice is oscillatory), but is the envelope of worst voltage situations to be considered (for being connected or not) against time after initiation of the network fault.

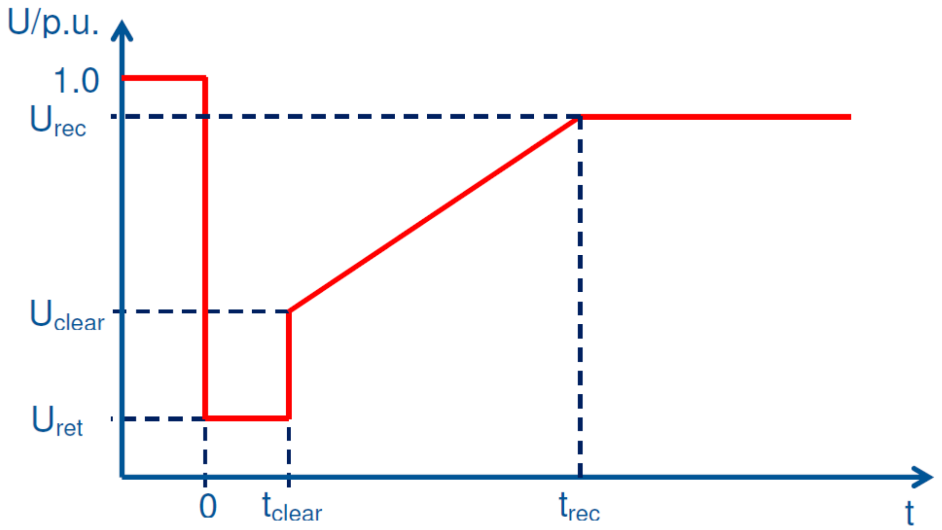


Figure 10. Generic FRT profile specified by the voltage at the connection point during and after a network fault (EWEA 2012).

<u>Active Power Frequency Response (dynamic stability studies)</u>: With active power frequency response, wind turbines provide an active power response in a direction, which assists recovery of the target system frequency, when network frequency changes. Thus, the frequency response capability is related to the system needs of frequency stability. Active power frequency response can be further divided in (a) continuous response (also called frequency sensitive mode) or (b) a proactive response acting from a specified deviation (threshold) of the system frequency (also called limited frequency sensitive mode). Technically, the active power frequency response capability enables the wind plant in principle to participate in system reserves provision in different time scales. Given the control feature installed in the wind turbines, the actual technical feasibility for providing a specified amount of upward response is dependent on the wind conditions at the moment that the response has to be given, as well as on the level of de-rating applied by the wind plant operator. The cost for providing this service will mean curtailed wind power generation, so it is not usually meant to be operated all the time, only in situations where more cost effective frequency response is not available, or operated in a way that only downward reserve is given when needed.

<u>Inertial Response (dynamic stability studies)</u>: With inertial response, wind turbines mimic the behaviour of synchronous generators, which, by their rotating mass inertia, oppose system frequency changes. Because power electronic converters (and direct current (DC) lines)

inherently do not display such behaviour, situations of large wind penetration may lead to diminished capability of the system to maintain frequency stability. Inertial response can be considered as a special case of active power frequency response, but is listed separately because some grid codes make the distinction, and because it sometimes may involve specific wind turbine control features. The control feature yielding an active power response intended to limit the rate of change of system frequency is a special form of frequency stability support complementary to the above-listed active power frequency response. It can be helpful to support the stability following a sudden generation loss in the system or a sudden surge (or drop) of demand.

2.2 Load Data

Hannele Holttinen, Emilio Gomez, Enrico Maria Carlini

Load data should be synchronous to wind data to capture any underlying correlations, and with the same time step (usually hourly, or 10–15 minutes). Load data has diurnal, weekly, and usually also seasonal patterns that can in principle be used to simulate time series data—simulated data is easier to generate than data for wind power generation. Load data is also usually quite straightforward to up-scale to future demand time series with demand growth assumptions, although more detailed information about potential changes in load patterns would be needed if these are anticipated.

It is essential for capacity value calculations to capture the correlations of wind power in extreme cold spells (for winter peaking systems) or heat waves (for summer peaking systems) using real data from several years. For unit commitment and economic dispatch (UCED) simulations, a year or selected representative weeks from each season can be sufficient, but using several years of data is recommended. For load flow and dynamic calculations, knowledge of representative peak and low load situations is sufficient, but different load cases with wind power levels that can produce challenging situations are needed on top of studying only peak and low load situations.

Load forecast data is needed for UCED modelling and for scheduling energy transfer in advance. In order to allocate reserves, uncertainties of the forecast, together with other uncertainties of the power system, has to be considered.

If historical load and load forecast time series data are not available from the system operators, they can be simulated. Forecasts of load are usually based on the time series technique, autoregressive-moving-average model (ARMA), or using more complex methods as expert systems (Rahman and Bhatnagar 1988), artificial neural networks (Bakirtzis et al. 1996; Chen et al. 2001), or hybrid methods (Song et al. 2006). With regard to uncertainties of load forecasts, error in forecast is usually modelled through a Gaussian distribution with a mean of zero (Doherty and O'Malley 2005), so that the only parameter needs to be set is the standard deviation of the load forecast error, which depends on the forecast period.

Network-based studies will also require assignment of the regional distribution of load and wind generation; the nature of this distribution may influence the simulation results obtained.

Dynamic models of load: The load itself also has dynamic characteristics, including sensitivity to frequency and voltage variations, and encompassing motor loads with inertia. Ideally, the load representation should vary with time of day, time of year, and perhaps be regionally distributed, making it particularly difficult to represent accurately.

2.3 Transmission Grid Interconnections

Enrico Maria Carlini, John Olav Tande, Hannele Holttinen

The level of input data will be different for different models:

- For power (resource) adequacy and loss-of-load calculations, the transmission grid is not usually taken into account. If there are concerns about bottlenecks in transmission during critical peak load situations, the loss-of-load probability can be calculated for different sub-areas. However, it is important to clearly state assumptions regarding the interconnections (NERC 2011). Ibanez and Milligan (2012) show how critical the assumptions regarding interconnected systems can be.
- For UCED, there are two approaches. The first is to use copperplate (i.e. assuming perfect transmission) inside areas and model only the key transmission paths between areas or transmission zones. In regions that use locational marginal pricing, such as market areas in the United States, it is common to develop a nodal transmission model that has more detail of the transmission network. UCED models are evolving to include also transmission, and DC load flows are available in several models, increasing the accuracy of the model. In either case, it is challenging to take into account the flexibility option from neighbouring areas through interconnectors—assuming a completely flexible interconnection capacity at all times will probably overestimate the flexibility available; not taking into account an existing interconnection will underestimate the flexibility available. These are important assumptions impacting the results (Holttinen et al. 2009).
- For network models, normally a large area transmission system is considered, or a smaller regional area with a distribution grid. The representation of the network is by topology, line rating, and impedance. High-Voltage Direct Current (HVDC) connections, reactive compensation units, (phase shifting) transformers, dynamic line rating, connected loads, and generation must also be adequately represented depending on the scope of study (i.e., steady state power flow or dynamic/transient).

A summary on the main dynamic modelling schemes is provided in CIGRE (2007).

2.4 Power Plant Data

Hannele Holttinen, Emilio Gomez, Frans van Hulle, Enrico Maria Carlini

The behaviour of remaining power plants and their responses to increased variability in the power system must be accurately described by the input data. Again, the level of detail will vary for different simulations. The future power plant mix might be altered from the current one, and the capabilities of the power plants may be different (see also Chapter 3.1 on portfolio set-up).

Wind power integration studies will be influenced especially by the availability of flexible (quick-start and high-ramp-rate) units. The merit order can change, as prices for different fuels used in the generation mix can change considerably. These assumptions will also drive conclusions regarding emission and carbon abatement.

The data for thermal and hydro power plants for different simulations are as follows:

- For estimating the capacity value of wind power and power adequacy of future systems, the forced outage rates of all power plants is the main input. The planned outages for maintenance can be scheduled not to coincide with critical peak load times, so only the forced outage rates per power plant are usually needed. There may be some cases with high penetration levels of wind power where the adequacy during shoulder seasons when there are planned outages needs to be studied also. Conventional generation uncertainty can be represented by the capacity outage table computed using the unit's outage replacement rate. The distribution of the power station outages should be adapted to the future power plant mix.

- For UCED modelling, economic data for merit order (fuel prices, efficiency curves) and technical data regarding flexibility (ramping capabilities, start-up times, and minimum on-line requirements and costs) are the main inputs. Outage risks are included to these studies in order to estimate reserve requirements. For reserve requirements, the individual probabilities of failure occurrence should be within the same time frame than for the other uncertainties of load and wind. Often the uncertainties are estimated by distributions; for example, thermal unit outages are modelled through a Poisson distribution (Doherty and O'Malley 2005). For hydro power plants with reservoirs or pumping possibilities, the constraints of the river systems need to be taken into account.
- For dynamic calculations, the dynamic behaviour and capabilities are modelled.

Dynamic models of conventional and wind generating units: The technical performance of both renewable and non-renewable generation to support high levels of wind generation is clearly important. Particularly, at higher wind penetration levels, validated and comprehensive wind turbine / wind power plant models will be required to accurately assess the dynamic power system characteristics (Coughlan et al. 2007; NERC 2009). For existing generating units, both conventional and from renewable energy sources, it is, therefore, essential that simulation models of individual components have been fully validated before analysis begins. On the contrary, for new generation power plants, as explained in (CIGRE 2007), generic models can be adopted. At the planning stage, a further complexity is added since in many cases the planner is not aware of the specific equipment that will be installed, particularly the control schemes associated to the new conventional and renewable generating units. Generic models of synchronous generation-based plant are well established, and have been developed and validated over many decades. However, it remains the case that the dynamic characteristics of individual units should be compared against actual responses, as available.

2.5 Demand-Side Management and Storage

Juha Kiviluoma, Hannele Holttinen, Enrico Maria Carlini

Demand-side management, particularly demand response (DR), and electricity storage are possible sources of flexibility for future power systems with large amounts of variable generation. They can often offer quite fast response and are therefore candidates for a wide spectrum of power system services. The most obvious uses are in energy balancing and peak load shaving, but they can also be used for different reserves, reactive power management, and congestion management. They can also provide reactive power management and congestion management in future distribution grids exhibiting more observability and control.

DR and electricity storage will impact portfolio development and production cost simulations and should also be used in capacity value estimation. In production cost simulations, it is important to take into account the temporal restrictions of DR and storages. Many forms of DR can be used only for some time before they need to be turned on again (e.g., many industrial processes and space heating) and require a recovery period after that. Some DR can only shift energy use from one period to another. Electricity storages have a limited storage size that constrains their use. These factors become especially important when uncertainty is included—and it should be included, since otherwise the use of DR and storage will be more optimal than is actually possible. The storage technologies can also have an impact on transient stability and long-term dynamics of power systems. The modelling of storage devices that are seen as equivalent at the high-voltage or extra-high-voltage busbars are further discussed in CIGRE TB TF 38 01.10 (2001), which explains the main characteristics of various storage technologies like fuel cells, superconducting magnetic energy storage, battery energy storage, and flywheels.

DR is not a single technology. There are multiple, very different possible sources of DR, which have different costs and constraints. From the modelling perspective, the challenge is to collect reasonable data about the possibilities of DR in the future. While there is lot of uncertainty on what might constitute future DR, there are some specific options to consider. When studying the impacts of large-scale wind power, it is probably best to concentrate on DR sources that could offer relatively large amounts of MW and/or MWh. These usually include some industrial loads and commercial loads as well as heating and cooling needs in households and other buildings. A further step would be to include the possibility of large fleets of electric vehicles with controllable charging and possibly vehicle-to-grid technology. Industrial loads typically have a high variable cost because it is expensive to idle industrial processes. However, they may be large MW sources, and it can be cost-efficient to equip some of them with very fast response capabilities for the purpose of primary reserve. They can also be useful in peak load situations. There may also be industrial loads with some form of process storage available that could therefore offer short-term flexibility with much lower variable costs. DR from commercial and office buildings could control cold storage or lighting. Heating and cooling of commercial, office, and households is something that could offer relatively large amounts of DR; however, this is very dependent on how the systems have been implemented and what energy sources they use. Hot or cold media are easier to store than electricity and therefore electrical heating and cooling linked with thermal storage are good candidates for DR (Kiviluoma and Meibom 2010).

For making future DR estimates, there are some publications available. Faruqui and Sergici (2010) have surveyed 15 demand response experiments where household electricity customers have received some form of compensation for reducing demand (including time-of-use pricing and critical-peak pricing). Time-of-use pricing resulted in modest reductions of 3–6% while critical-peak pricing had a much higher effect of 13–20%. Similarly empirical results from demand response programs in the United States have achieved a level of 3–9% of potential reduction in peak demand (Cappers et al. 2010). This includes industrial demand response as well as household demand response (Kirby, 1999). Widergren (2009) also points out that aggregating demand response from households will include significant uncertainties in terms of actual delivery. These have to be understood and addressed.

Most forms of electricity storage are rather expensive for balancing the energy between low and high wind generation periods, because of high investment costs and a relatively low number of cycles per year. Pumped hydro, and possibly compressed air energy storage (CAES), can be an exception to this. However, electrical storage can have a very rapid response and can possibly provide some other system services at competitive prices. Electricity storage costs have been evaluated at least in Schoenung (2011) and Divya and Østergaard (2009) for batteries as well as Deane et al. (2010) for pumped hydro power. Battery and flywheel energy storage devices have been demonstrated in PJM and NYISO, respectively.

2.6 Checklist of Recommendations for Input Data

Recommendations regarding the input data are summarised in Table 2.

Table 2. Recommendations for input data needed for the integration study components.

	Capacity Value / Power (resource) Adequacy	Unit Commitment and Economic Dispatch (UCED)	Load Flow	Dynamics
Wind Power	Hourly time series of 6–10 years, distributed wind power covering the area	5-minute to hourly time series of at least 1 year, distributed wind power covering the area	Wind power capacity at nodes, high and low generation and load snapshots, active and reactive power	Wind power capacity at nodes, high and low generation snapshots, dynamic models of turbines, operational strategies
Wind Power short term Forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	Will be needed in future	Not needed
Load	Hourly time series of 6–10 years	5-minute to hourly time series of at least 1 year	Load at nodes, snapshots relevant for wind integration	Load at nodes, high and low load snapshots, dynamic capabilities
Load Forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	Will be needed in future	Not needed
Network	Cross border capacity, if relevant	Transmission line capacity between areas and interconnectors to neighbouring areas	Network configuration, circuit passive, and active parameters	Network configuration, circuit parameters, control structures
Power Plants	Rated capacities and forced outage rates	Minimum on-line capacity, start-up time, ramp rate, efficiency curve, fuel prices	Active and reactive power capabilities, system dispatch	Dynamic models of power plants

References

Bakirtzis, A.G.; Petridis, V.; Kiartzis, S.J.; Alexiadis, M.C.; Maissis, A.H. (1996). "A Neural Network Short Term Load Forecasting Model for the Greek Power System." *IEEE Transactions on Power Systems* (11:2); pp. 858–863.

Cappers, P.; Goldman, C.; Kathan, D. (2010). "Demand Response in U.S. Electricity Markets: Empirical Evidence." *Energy* (35:4); pp. 1526–1535.

Chen, H.; Cañizares, C.A.; Singh, A. (2001). "ANN-Based Short-Term Load Forecasting in Electricity Markets." *IEEE Power Engineering Society Winter Meeting*, 28 January–1 February, Columbus, Ohio, United States.

CIGRE (Conseil International des Grands Réseaux Électriques). (2007). "Application and Required Developments of Dynamic Models to Support Practical Planning." Technical Brochure 312, CIGRE Working Group C1-04. Available on www.e-cigre.org.

CIGRE (Conseil International des Grands Réseaux Électriques). (2001). "Modelling New Forms of Generation and Storage." Technical Brochure TF 38 01.10. Ref. No. 185.

Coughlan, Y.; Smith, P.; Mullane, A.; O'Malley, M. (2007). "Wind Turbine Modelling for Power System Stability Analysis—A System Operator Perspective." *IEEE Transactions on Power Systems* (22:3); pp. 929–936.

Deane, J.P.; Ó Gallachóir, B.P.; McKeogh, E.J. (2010). "Techno-Economic Review of Existing and New Pumped Hydro Energy Storage Plant." *Renewable and Sustainable Energy Reviews* (14:4); pp. 1293–1302; doi:10.1016/j.rser.2009.11.015.

Divya, K.C.; Østergaard, J. (2009). "Battery Energy Storage Technology for Power Systems—An Overview." *Electric Power Systems Research* (79:4); pp. 511–520; doi:10.1016/j.epsr.2008.09.017.

Dobschinski, J.; E. De Pascalis; A. Wessel; L. von Bremen; B. Lange; K. Rohrig; Y.-M. Saint-Drenan. (2010). "The potential of advanced shortest-term forecasts and dynamic prediction intervals for reducing the wind power induced reserve requirements. *Proceedings of European Wind Energy Conference EWEC2010, 20-23rd April, 2010*, Warsaw, Poland.

Doherty, R.; O'Malley, M. (2005). "A New Approach to Quantify Reserve Demand in Systems with Significant Installed Wind Capacity." *IEEE Transactions on Power Systems* (20:2); pp. 587–595.

European Wind Energy Association (EWEA). (2012). Technical note that for the public consultation on the ENTSO-E Network Code RfG, March 2012, EWEA.

Faruqui, A.; Sergici, S. (2010). "Household Response to Dynamic Pricing of Electricity: A Survey of 15 Experiments." *Journal of Regulatory Economics* (38); pp. 193–225; doi:10.1007/s11149-010-9127-y.

Garcia Casado, M. Presentation of Spanish TSO REE in UVIG Forecasting Workshop, SLC, 2013 (will also appear in Holttinen, H. et al, Managing Variability with Flexibility. IEEE PES magazine Nov 2013)

Gibescu, M.; Kling, W.L.; Ummels, B.C.; Pelgrum, E.; Van Offeren, R.A. (2009). "Case Study for the Integration of 12 GW Wind Power in the Dutch Power System by 2020." *CIGRE/IEEE PES Joint Symposium on the Integration of Wide-Scale Renewable Resources into the Power Delivery System*, 29–31 July, Calgary, Canada.

Giebel, G.; Sørensen, P.; Holttinen, H. (2007). "Forecast Error of Aggregate Wind Power." Risø-I-2567. Roskilde, Denmark: Risø National Laboratory.

Hasche, B.; Keane, A.; O'Malley, M. (2011). "Capacity Value of Wind Power, Calculation, and Data Requirements: The Irish Power System Case." *IEEE Transactions on Power Systems* (26:1); pp. 420–430; doi:10.1109/TPWRS.2010.2051341.

Holttinen, H.; P. Meibom; A. Orths; F. van Hulle; B. Lange; M. O'Malley; J. Pierik; B. Ummels; J.O. Tande; A. Estanqueiro; M. Matos; E. Gomez; L. Söder; G. Strbac; A. Shakoor; J. Ricardo; J.C. Smith; M. Milligan; and E. Ela. (2009). *Design and operation of power systems with large amounts of wind power*, VTT Research Notes. 2493, Espoo, Finland.

Holttinen, H.; Kiviluoma, J.; Estanqueiro, A.; Gómez-Lázaro, E.; Rawn, B.; Dobschinski, J.; Meibom, P.; Lannoye, E.; Aigner, T.; Wan, Y.-H.; Milligan, M. (2011). "Variability of Load and Net Load in Case of Large Scale Distributed Wind Power." In *Proceedings of 10th International*

Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 25–26 October, Århus, Denmark.

Ibanez, E.; Milligan, M. (2012). "Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power." NREL/CP-5500-53482. Golden, CO: National Renewable Energy Laboratory.

IEC (International Electrotechnical Commission). (2012). "Wind Turbines Part 27-1: Electrical Simulation Models for Wind Power Generation." IEC 61400-27 Committee Draft 88/424/CD.

King, J.; Kirby, B.; Milligan, M.; Beuning, S. (2012). "Operating Reserve Reductions from a Proposed Energy Imbalance Market with Wind and Solar Generation in the Western Interconnection." NREL/TP-5500-54660. Golden, CO: National Renewable Energy Laboratory.

B. Kirby and E. Hirst, *Load as a resource in Providing Ancillary Services*, American Power Conference, Chicago, Illinois, April 1999.

Kiviluoma, J.; Meibom, P. (2010). "Influence of Wind Power, Plug-In Electric Vehicles, and Heat Storages on Power System Investments." *Energy* (35:3); pp. 1244–1255.

Lange, B.; Ü. Cali; R. Jursa; R. Mackensen; K. Rohrig; F. Schlögl. (2006). Strategies for Balancing Wind Power in Germany. DEWEK 2006, Bremen, Germany.

Menemenlis, N.; Huneault, M.; Robitaille, A. (2012). "Computation of Dynamic Operating Balancing Reserve for Wind Power Integration for the Time-Horizon 1–48 Hours." *IEEE Transactions on Sustainable Energy* (3:4); pp. 692–702.

Menemenlis, N.; Huneault, M.; Robitaille, A.; Holttinen, H. (2012). "Common Characterization of Variability and Forecast Errors of Variable Energy Sources and Their Mitigation Using Reserves in Power System Integration Studies." *11th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, 14–15 November, Lisbon, Portugal.

NERC (North American Electric Reliability Corporation). (2011). *Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning*. Princeton, NJ: NERC. Available at http://www.nerc.com/docs/pc/ivgtf/IVGTF1-2.pdf.

Rahman, S.; Bhatnagar, R. (1988). "An Expert System Based Algorithm for Short Term Load Forecast." *IEEE Transactions on Power Systems* (3:2); pp. 392–399; doi:10.1109/59.192889.

Schoenung, S. (2011). "Energy Storage Systems Cost Update—A Study for the DOE Energy Storage Systems Program." SAND2011-2730. Albuquerque, NM, and Livermore, CA: Sandia National Laboratories.

Söder, L; Abildgaard, H.; Estanqueiro, A; Hamon, C.; Holttinen, H.; Lannoye, E.; Gomez Lazaro, E.; O'Malley, M.; Zimmermann, U. (2012). Experience and challenges with short term balancing in European systems with large share of wind power. *IEEE Transactions on Software Engineering*.

Song, K.B.; Ha, S.K.; Park, J.W.; Kweon, D.J.; Kim, K.H. (2006). "Hybrid Load Forecasting Method with Analysis of Temperature Sensitivities." *IEEE Transactions on Power Systems* (21:2); pp. 869–876.

Widergren, S.E. (2009). "Demand or Request: Will Load Behave?" *IEEE Power & Energy Society General Meeting*, 26–30 July, Calgary, Alta; doi:10.1109/PES.2009.5275506.

Wolff, M.; B. Lange; D. Braams; L. Hofmann; M. Rosin. (2007) "Control strategies for wind farms in meshed grids." *Proceedings of the EWEC 2007*, Milano, Italy.

3 Portfolio Development and System Management

Lennart Söder, Hannele Holttinen, Michael Milligan, Mark O'Malley, Juha Kiviluoma

This chapter describes the blue/red boxes (Figure 11 red circle) of the wind integration study components flow chart. It covers the setup of the study and main assumptions regarding portfolio development, including transmission scenarios and system management procedures.

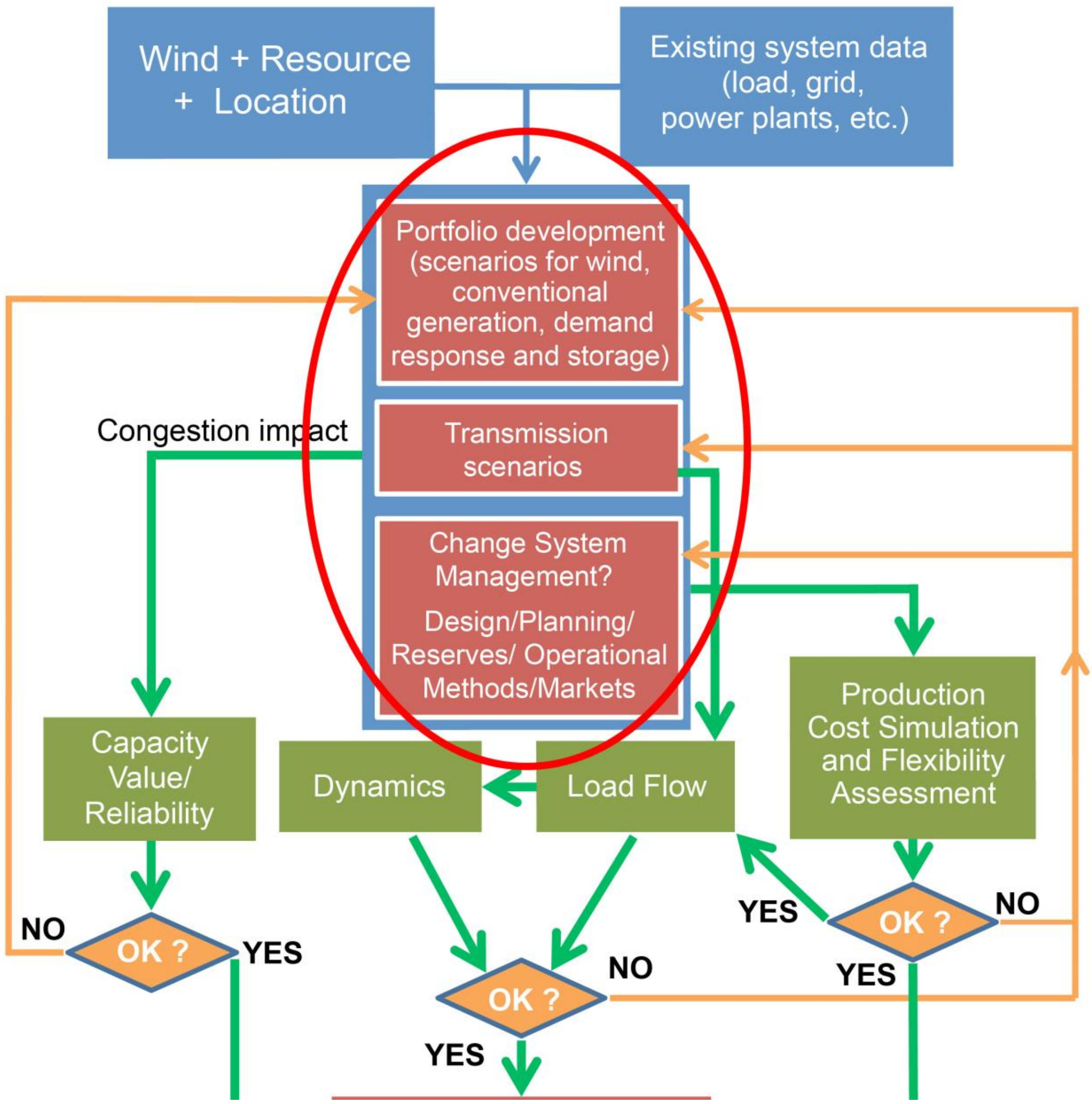


Figure 11. Wind integration study components: portfolio development, transmission scenarios, and changes in system management

The purpose of a wind integration study and the main setup chosen will have crucial impacts on the results. Often the motivating questions relate to the technical and cost impacts of wind power; sometimes they also relate to how much wind is technically possible, or how much is possible without changes in system. Different goals mean different approaches and can also impact the methods. In most cases, the higher penetration levels of wind power will be relevant for a future (not current) system. Transmission capacity, reserves, and operational practices are important inputs to wind integration study calculations. Important iterations will feedback from later phases of the integration study simulations because changing generation and transmission, or operational practices (including how reserves are allocated), may be required to cost-effectively integrate larger amounts of wind power.

The portfolio of generation plants, transmission capacity, and operational practices are all important inputs to wind integration study calculations. Some things in the power system assumptions may need to be changed before simulating the impacts of wind power: transmission capacity, reserve allocation, and operational practices, including electricity market design. The main decisions regarding portfolio development are 1) what kind of system is studied—now or in the future—and 2) how wind power is added, replacing something or keeping the remaining system the same. The assumptions regarding the available flexibility, technically, and operationally are important for results on the balancing needs. The setup chosen for the study may give rise to limitations as to how much wind power can cost-effectively be integrated.

3.1 Generation Portfolio and Transmission Scenarios

Lennart Söder, Michael Milligan, Hannele Holttinen

The study assumptions regarding (future) generation and transmission will have a crucial impact on the results. The main issues to decide in the study set-up are:

- What kind of system is being studied—the current system or a future scenario or scenarios
- How wind power is added—replacing some existing generation, adding to an otherwise static system, adding simultaneously with a block load of same energy content, or through a portfolio development (possibly optimisation) process
- Assumptions regarding available flexibility, both technical and institutional

When compiling a future power system mix, different assumptions can be made regarding energy, emission, and carbon policies. Considerations regarding generation portfolio include:

- What will the composition of the generator fleet be in the future year? If large amounts of wind power are expected, then conventional base load units (with high investment cost and low operational costs) may become uneconomic due to too few hours to operate, and they may be replaced by plants with lower investment costs, higher operational costs, and more flexible generation. Reducing inflexible base load units will make a large difference in the ease or difficulty in integrating wind power.
- What are the relative prices for different fuels used in the generation mix? The answer will determine which generating units are on the margin, and therefore which generating units are displaced by wind power, and which generation cycles more frequently to help manage the increase in variability and uncertainty. This will also impact the results on operational cost savings.
- Will there be significant quick-start units in the future system? If so, the unit commitment problem is not so complex, nor is it as important. On the other hand, if there is a significant amount of slow-start generation, or generation with high minimum run levels, unit commitment will become a more significant binding constraint

The generation scenario and power plant mix chosen will have to provide reliability regarding the adequacy of power for all peak load situations. Therefore, the wind integration study component “capacity value/reliability” has an iteration loop back to the generation portfolio in Figure 1.

Transmission scenarios are an important input for simulations, and they are also one output of the study: how much new transmission is needed to accommodate the foreseen wind power. This usually means iterations from the load flow simulations back to the transmission scenarios. Meeting ambitious targets that have been set for wind energy will often require upgrades to the existing transmission infrastructure and the construction of new lines. The new transmission assets will not just transmit wind generation; they will also enhance the security of supply and facilitate the connection of other power generation and implementation of the electricity market. Therefore, assigning costs and benefits using a causal framework is not likely to be accurate.

When congestion in transmission is seen from the simulation, then more transmission may be warranted. However, if the congestion is not severe, curtailing wind power or maximising the use of existing lines may be more cost effective than building new lines.

Transmission is an enabler to wind integration, both as a means to get the electricity to where it is consumed, but also enabling the sharing of flexibility between neighbouring areas and contributing to more economic wind integration. Operational practices influence how much of the flexibility is accessible in practice.

The main recommendations based on these issues are as follows:

1. When studying small amounts of wind power (penetration levels where wind share in energy is less than 5–10%), wind power can be studied by adding wind to an existing or foreseen system.
2. For larger penetration levels, changes in the assumed remaining system may be necessary, taking into account flexibility needs and additional network infrastructure.

3.2 Operational Practices and Markets

Michael Milligan, Hannele Holttinen, Juha Kiviluoma

Operational methods and markets may need to be assessed as part of the study to determine whether the current operational practices and market rules allow for reliable and cost-efficient integration of wind power at increasing penetration levels. One example of this is the Western Wind and Solar Integration Study (WWSIS), where it was assumed that balancing areas in the WestConnect sub-regional area of the Western Interconnection of the United States would develop a high level of coordination in operations, including UCED (WWSIS 2010). Depending on the geographic spread of the wind energy in that study, the existing operating practice may not be effective in integrating 35% wind and solar energy.

For systems undergoing a first-ever integration study, the current operating practices may be used as a starting point, to establish a baseline from which changes can be evaluated. Another approach is to use existing practice in the study to determine whether this is sufficient to integrate the studied level of wind energy. If operational problems emerge from the simulation, then alternative assumptions and scenarios could be developed to assess whether new methods of operation can be used to more efficiently integrate wind energy.

Scheduling and dispatch practice and unit commitment practice can have a significant impact on the efficient integration of wind energy. Rolling unit commitment (Tuohy et al. 2009) has been shown to help with integration because new information can be incorporated into operational decision-making when it becomes available, allowing for changes in the unit commitment stack, subject to physical constraints. Larger electrical balancing areas and faster economic dispatch can have an impact on reserve requirements, and can also allow for access to more flexibility compared to smaller balancing areas and longer dispatch periods (King et al. 2011).

In some cases, it may be economic to curtail wind generation when there are transmission constraints or other constraints imposed by the inability to turn down large base-load units that do not occur frequently.

Operational practice among different power system operators varies significantly, and this can complicate integration analysis. There are differences in the time periods associated with UCED, and there are also differences in the forecast period and notification period used to take a system snapshot and perform the processes necessary to execute movement to a new dispatch point. The definitions and availability of the various ancillary services (such as various reserve types) are not the same from system to system, and operational reliability metrics can vary. In addition, the way that ancillary services are procured will depend on whether there are markets, and whether those markets are robust.

Operational methods may change with the addition of transmission and/or more flexible generation (e.g., new transmission interconnection to neighbouring systems may enable access to more flexible generation, and at the same time reduce the overall need for flexibility in the combined systems). New, quick-start, fast-ramping generation may enable shorter unit commitment time frames.

Changes may be made in forecasting practice. In tandem with more accurate, short-term wind forecasts, markets may be able to shorten the notification period (King et al. 2011). Integration studies might investigate these issues to determine the value of these market characteristics on the ability to integrate wind power.

Where market structures are inhibiting access to flexibility, they may need to be changed (such as changing dispatch times towards faster markets – shorter dispatch time steps). Most existing markets include an energy market, and some include balancing/regulation markets. In the United States, there are at least two independent system operators (ISO) currently investigating a potential new market for some form of ramping product, which would presumably complement the existing energy markets (California ISO and Midwest Independent TSO). Another example is the North European Nordic market where TSOs from four countries cooperate and use the cheapest regulating bids to correct intra-hour imbalances for the total system area, considering all transmission limits: both internally in the countries as well as limits between the countries.

Key operational and market issues include:

- What will be the institutional setting of the future time period to be analysed? Will markets evolve to include products that enhance flexibility, or will fast dispatch/balancing be sufficient? Will there be reserve markets over different time scales? Will there be any type of operational consolidation or dynamic scheduling (of generation, load, or imbalance) that will have an impact on integration? Will there be broader reserve-sharing regions? Is it allowable to deploy contingency reserves for significant wind ramp events, and if so, what are the criteria for doing so? What is the assumption regarding balancing areas/zones, and what is the appropriate modelling approach to account for interchange that correctly captures actual (or future) practice?
- Will reliability-based balancing criteria be the same in the future? For example, there have been Reliability-based Control field trials in the United States, which, if adopted, would eliminate the current Control Performance Standard 2 and likely result in significantly reduced requirements on balancing units. This would have a significant impact on wind integration studies.

The main recommendations based on these issues are as follows:

1. Existing operational practice can be used as a starting point when studying small amounts of wind power (penetration levels where wind share in energy is less than 5–10%).
2. For higher penetration levels, additional scenarios or operating practices should be studied. Market structures/design to enable operational flexibility, potentially including capacity markets should be assessed.

3.3 Reserve Allocation – Estimating Changes Due to Wind Power

Michael Milligan and Hannele Holttinen

The impact that wind energy has on procuring operating reserves is an on-going area of research, taking the uncertainty of wind power into account while aiming for both reserve adequacy and economic provision (Holttinen et al. 2012). System operators carry reserves to balance load and generation, and to respond to outages.

System reserves are allocated (dimensioned and scheduled) for a diverse range of conditions and reserve allocation considers reserves responding across multiple timescales. Systems also require reactive power reserve for voltage support and a long-term reserve (planning reserve). These reserves are allocated to ensure resource adequacy during peak load situations. However, these aspects are generally not considered in analyses for increased reserve requirements due to wind power—reactive power reserve can contribute to transmission grid studies and planning reserve can contribute to capacity value/power (resource) adequacy studies.

Reserves that are held in case of generator outage or transmission line trip are called contingency reserves. Typically the level of contingency reserve that is needed depends on the largest generator or transmission line in the system, and wind power does not have a direct impact on this amount. Other reserves are held to manage variability and uncertainty (beyond the uncertainty associated with a unit tripping offline), again depending on the system and the risk tolerance of the system operator. For these reserve categories, terminology varies in different power systems. Reserves that operate automatically to keep the frequency close to nominal are called primary and secondary reserves in Europe, and regulating reserves in the United States. Manually activated reserves are activated when needed to relieve primary and secondary reserves, correct the area control error (ACE), and meet expected changes in the system balance (from minutes to a few hours. These are called tertiary reserves in Europe and load-following reserves in the United States) (Milligan et al. 2010). Generally, reserves that are needed more than 10 minutes in the future can be provided by either spinning or non-spinning resources—these are not distinguished unless in this report discussion is specific enough to require it.

The term “operating reserve” is defined here as the active power capacity that can be deployed to assist with generation / load balance and frequency control. Impacts on contingency reserve that is used to cover large failures is often ignored because it is not generally affected by wind power and most systems do not plan contingency reserves to help manage large wind power ramp events (Holttinen et al. 2012; Gil et al. 2011). To determine reserve one must consider response needs across multiple timescales: a simple approach distinguishes reserve operating automatically (in seconds) and reserve activated manually when needed (from minutes to a few hours).

It is important to note that the time steps chosen for dispatch and market operation can influence the reserve requirements. For example, markets with a 5-minute scheduling resolution can automatically extract balancing needs from the generators that must ramp to achieve proper position for the schedule for the next market period (Kirby and Milligan 2008; Milligan et al. 2011).

It should also be noted that an increased level of reserve due to wind power may be supplied by already present conventional generators that are used to supply energy in the non-wind case, and therefore supply less energy and more reserve in the wind case (for example, in a situation with high wind power production, other power plants are running on a comparatively low level and could then increase their output to compensate for fast wind power decrease / load increase). This is a critical distinction, i.e. that an increased need of reserves does not necessarily lead to need of new reserve capacity. A correct modelling is crucial for a realistic estimation of the impact on reserve capacity when the amount of wind power increases. The computation of reserve requirements requires estimates of the uncertainty and variability of demand, wind generation, and other generation sources. Some reserves may be allocated for real time variability only. For wind power, the forecast horizon is a crucial assumption because the uncertainty at shorter time scales will reduce more significantly than that for demand. The forecast data must be consistent with operating practice, which will likely be somewhat unique for each system. In some cases, there may be anticipated future changes in operating procedures, such as significant changes in transmission, balancing methods, or unit commitment practice. Some integration studies may evaluate how these new practices would change the way that wind energy could be integrated into the system. In such studies, it is important to ensure that input data are consistent with the operating practice that will be modelled in the study.

3.3.1 Recommended Methods

A common approach is to compare the uncertainty and variability before and after the addition of wind generation. Adding wind generation means allocating additional reserves to maintain a desired reliability level. Traditionally, the term “reliability” refers to assuring resource adequacy to accommodate rare events in long-term planning, and also the ability to maintain the system operationally. In the context considered here, reliability concepts are applied to the operational planning horizon, which spans a time frame from a few minutes to a few days ahead, and thus is referred to as short-term or operational reliability.

Several methods can be used to calculate the impact of wind generation on operating reserves (Menemenlis 2012; Milligan et al. 2010; Ela et al. 2010; Ela et al. 2011; Holttinen et al. 2012).

Generally, recommended steps include the following:

1. The risk of insufficient reserve (i.e., the probability that the scheduled generation plus reserves will not be sufficient to supply the load) must be identified. If the risk is realised, power is imported from neighbouring balancing areas. For example, one might choose to cover 95% of the variations in net load (load minus wind power) of the balancing area, based on existing operating practice of balancing area reliability metrics in use (like control performance standard in the United States). When considering a whole synchronous system without interconnections, the risk level should correspond to an acceptable loss of load expectation due to insufficient operational reserves.
2. Operating reserves should be calculated for the appropriate time scales, matching existing operational practice. Typically, different types of reserves are associated with (a) automatically responding in seconds-minutes and (b) manually activated in minutes-hour to several hours. When splitting the reserves into separate categories, it is essential not to double-count sources of variability or uncertainty; hence, care should be exercised in this process. If, e.g. the amount of 4-hour reserves increases then they normally include also the increase of 2-hour reserves

3. Simple statistical methods can be used to combine the variability and uncertainty from wind and load (and generation); however, assuming that load and generation errors can be represented by normal uncorrelated distributions and using standard deviation values (n-sigma method) will not be valid. Statistical methods can be altered to take this into account; for example, using a desired level of exceedence or by performing analysis to determine the appropriate distribution.
4. Net-load-related reserves should not be static. The variability and forecast uncertainties depend on meteorological conditions and vary over time. When wind power is generating at a low level of output, there is little need for up-reserve from conventional plants; constant reserve levels will lead to varying risk levels, and conversely, maintaining a constant reliability or risk level will require varying reserves. A further step is to consider the value at risk, which will also change depending on the power system state. It has also been found that wind power variability is generally highest in the mid-output range, as well as during storms, and dynamic reserve methods have been developed that build upon this information (EWITS 2010).
5. The cost and value of these reserves should be assessed in a probabilistic framework. The uncertainties involve the prices of the reserve resources, their probabilities of use, and expected benefits (Menemenlis et al. 2011).

There is a link between the availability of and need for reserves. Wind generation, when available, can be used for down regulation (decreased power output) when other more cost effective options have been depleted. For up regulation (increased power output) more wind power is usually lost, as this means operating with reduced output levels. At high wind levels, other power plants usually operate at a reduced level with the ability for up regulation.

Larger balancing areas can use the benefit of limited correlation between load and wind power changes in neighbouring areas. This means that the total amount of needed reserves for both areas is relatively smaller – assuming there are only limited transmission bottlenecks impeding trade of reserves.

3.3.2 Other Methods for Assessing Reserve Needs

Because of the evolution and anticipated further developments in reserve methods, there may be promising new methods developed. However, simple methods can result in unintended irrational reserve policies. We do not recommend methods with the following characteristics:

- Fixed level of operating reserve. This implies that up-reserve is held when it is not needed, and conversely, that down-reserve is also held when it is not needed. Although this may not have negative impacts on reliability, it incurs a needless additional cost to the system.
- Methods that do not consider the level of risk, whether implied or explicit. Although this is a corollary to the previous point, it is not the same. If a specific risk level is not taken into account, it might result in either too little reserve (an unacceptable level of risk) or too much reserve (more than could possibly be required).

3.4 Checklist: Portfolio Development and System Management

Checklist of Key Issues: Portfolio Development and System Management

- Generation and transmission scenarios:
  - When studying small amounts of wind power (penetration levels where wind share in energy is less than 5–10%), wind power can be studied by adding wind to an existing, or foreseen, system.
  - For larger penetration levels, changes in the remaining system may be necessary, taking into account flexibility needs and additional network infrastructure.
- Operational methods:
  - Existing operational practice can be used as a starting point when studying small amounts of wind power (penetration levels where wind share in energy is less than 5–10%). For higher penetration levels, additional scenarios or operating practices should be studied.
  - Assess market structures/design to enable operational flexibility.
- Reserve requirements/allocation method:
  - Input data: Synchronous wind and load time series (at least hourly) and wind/load forecast error distributions, possibly also generation outage distribution.
  - Choose level of risk based on existing operating practice; for example, to cover 95% of the variations in load and net load (load minus wind power) output.
  - Calculate for the appropriate time scales, corresponding to existing operational practice (like automatically responding in seconds-minutes, and manually activated in minutes-hour to several hours). Split the input data for these categories with care not to double-count sources of variability or uncertainty.
  - Combine variability and uncertainty from wind and load (and generation), keeping the same risk level before and after adding wind. Whatever statistical method applied, take into account that variability and uncertainty are not normally distributed. Using a desired level of exceedance, or determining the appropriate distribution is therefore recommended instead of using standard deviation.
  - With increasing penetration levels, use dynamic, not static reserves.

References

Ela, E.; Milligan, M.; Kirby, B.; Lannoye, E.; Flynn, D.; O'Malley, M.; Zavadil, B. (2010). "Evolution of Operating Reserve Determination in Wind Power Integration Studies." NREL/CP-5500-49100. Golden, CO: National Renewable Energy Laboratory.

Ela, E.; Milligan, M.; Kirby, B. (2011). "Operating Reserves and Variable Generation." NREL/TP-5500-51978. Golden, CO: National Renewable Energy Laboratory.

EWITS (Eastern Wind Integration and Transmission study). (2010). Prepared for the National Renewable Energy Laboratory. Available at http://www.nrel.gov/wind/news/2010/803.html.

Giebel, G.; R. Brownsword, G.; Kariniotakis, M.; Dernhard, C.; Draxl. (2011). The State of the Art in Short-Term Prediction of Wind Power: A Literature Overview. Deliverable D-1.2 of Anemos.plus. Available at http://www.prediktor.dk/publ/GGiebelEtAl-StateOfTheArtInShortTermPrediction_ANEMOSplus_2011.pdf.

Gil, A.; M. de la Torre; R. Rivas. (2010). “Influence of Wind Energy Forecast in Deterministic and Probabilistic Sizing of Reserves,” *9th International Workshop on Large-Scale Integration of Wind Power into Power Systems* as well as on Transmission Networks for Offshore Wind Power Plants, October 2010, Quebec, Canada.

Holttinen, H.; M. Milligan; E. Ela; N.Menemenlis; J. Dobschinski; B.Rawn; R.J. Bessa; D. Flynn; E. Gomez Lazaro; N. Detlefsen. (2012). “Methodologies to Determine Operating Reserves due to Increased Wind Power.” *IEEE Transactions on Sustainable Energy.*

King, J.; Kirby, B.; Milligan, M.; Beuning, S. (2011). “Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection.” NREL TP-5500-52330. Golden, CO: National Renewable Energy Laboratory.

Kirby, B.; Milligan, M. (2008). “Examination of Capacity and Ramping Impacts of Wind Energy on Power Systems.” NREL/TP-500-42-872. Golden, CO: National Renewable Energy Laboratory.

Menemenlis, N.; Huneault, M.; Robitaille, A. (2012). “Computation of Dynamic Operating Balancing Reserve for Wind Power Integration for the Time-Horizon 1–48 Hours.” *IEEE Transactions on Sustainable Energy* (3:4); pp. 692–702.

Menemenlis, N.; Huneault, M.; Robitaille, A. (2011). “Risk Coordination in the Computation of Operating Balancing Reserves for Wind Power Integration.” In *Proceedings of the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, 25–26 October, Århus, Denmark.

Milligan, M.; Donohoo, P.; Lew, D.; Ela, E.; Kirby, B.; Holttinen, H.; Lannoye, E.; Flynn, D.; O’Malley, M.; Miller, N.; Eriksen, P.B.; Gøttig, A.; Rawn, B.; Gibescu, M.; Gomez-Lázaro, E.; Robitaille, A.; Kamwa, I. (2010). “Operating Reserves and Wind Power Integration: An International Comparison.” NREL/CP-5500-49019. Golden, CO: National Renewable Energy Laboratory.

Milligan, M.; Kirby, B.; King, J.; Beuning, S. (2011). “The Impact of Alternative Dispatch Intervals on Operating Reserve Requirements for Variable Generation.” *10th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, 25–26 October, Århus, Denmark.

Tuohy, A.; Meibom, P.; Denny, E.; O’Malley, M. (2009) “Unit Commitment for Systems with Significant Wind Penetration.” *IEEE Transactions on Power Systems* (24:2); pp. 592–601.

WWSIS (Western Wind and Solar Integration Study). (2010) “Western Wind and Solar Integration Study.” Prepared by GE Energy. NREL report SR-5500-47434, May 2010 http://www.nrel.gov/docs/fy10osti/47434.pdf

4 Capacity Value

Andrew Keane, Lennart Söder, Michael Milligan, Hannele Holttinen

This section describes the first simulation box of the wind integration study components flow chart (Figure 12 red circle).

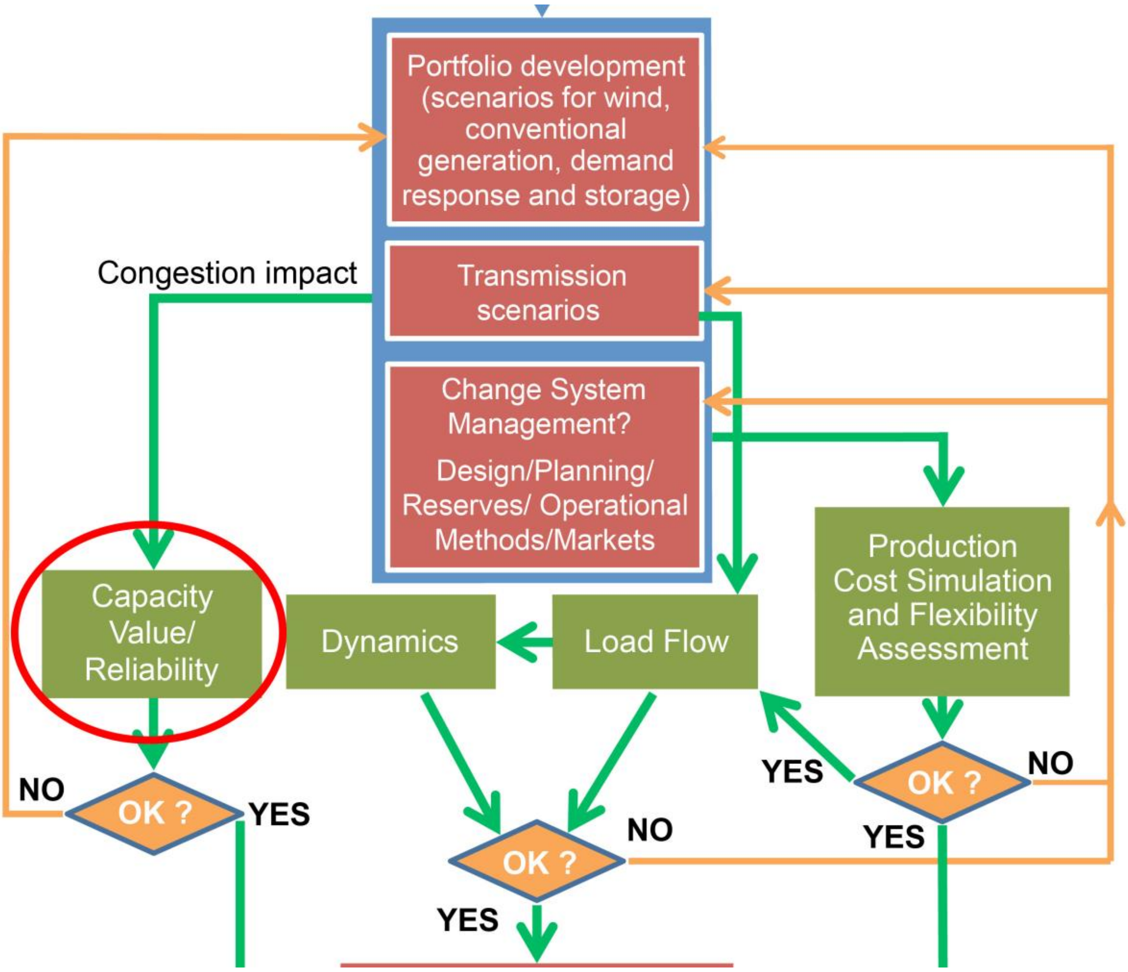


Figure 12. Wind integration study components: estimating capacity value of wind power.

Capacity value estimation has often been performed as a separate evaluation in wind integration studies. If the reliability (resource adequacy) target is not met by the power plant scenario, an iteration is applied to change the portfolio to include more generation capacity or less (or flexible) load. The capacity value calculation should recognise transmission limits when considering which area of the power system is being studied.

Power system reliability is divided into two basic aspects, system security and system adequacy. A system is secure if it can withstand a loss (or potentially multiple losses) of key power supply components, such as generators or transmission links. Generation system adequacy (often called "resource adequacy") refers to whether there is sufficient installed capacity to meet the electric load at some prescribed level of risk (Billinton and Allan 1996). This adequacy is achieved with a combination of different generators that may have significantly different characteristics.

Capacity value (or credit) can be defined as the amount of additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability (Keane et al. 2011). It is central to determining a system's generation adequacy. Capacity value is used by system engineers to assess the risk of a generation capacity deficit. In recent years, it has gained importance, in light of the increased uncertainty arising from wind power availability, which is a function of the local weather conditions.

Metrics used for adequacy evaluation include the loss of load expectancy LOLE, the loss of load probability LOLP, and the effective load carrying capability ELCC. LOLP is the probability that the load will exceed the available generation at a given time (in interconnected systems, this probability may instead refer to the probability of unintended import). This criterion only gives an indication of generation capacity shortfall and lacks information on the importance and duration of the outage. LOLE is the expected number of hours or days during which the load will not be met over a defined time period. The ELCC is a metric that can be used to denote the capacity value (Garver 1966).

Capacity value studies in various power systems have been undertaken utilising a variety of methodologies (see Holttinen et al. 2009 for comparisons). It is apparent from the methods described below that the capacity value is dependent on the method employed, but it also depends on the specific characteristics of the region/country—in particular, the characteristics of the wind regime and the characteristics of the demand profile (e.g., whether peak demand occurs in winter or summer). Some of the lower values reported are due to the lower average wind power production, but different methodologies used also explain the differences. Across systems, the general trend has been that wind's capacity value decreases with increasing generation capacities of wind.

The correlation between wind generation and peak load situations strongly influence the results. Hence, many years of synchronous load and wind data are needed. The resulting answer cannot be relied upon if sufficient data of the required quality is not available (Hasche et al. 2010). An important characteristic of wind power is its spatial diversity. This means that the capacity value increases relative to larger region sizes (Holttinen et al. 2009; NERC 2008)—larger areas decrease the number of hours of low wind output, due to the smaller probability of very low output across the whole system. The ELCC method also requires a complete inventory of conventional generation units' capacity and forced outage rates.

4.1 Methodologies and Models

The reliability level can greatly impact the capacity value of both conventional power and wind power (Clark et al. 2005). When the reliability level is lower and LOLE higher, there is relatively more value in any added capacity than in cases where LOLE is very low.

The recommended method for determining capacity value is the ELCC calculation as it determines the full net load ELCC. With modern computing power, this method is not overly time-consuming for moderately sized systems. This method contains approximations, but as it utilises the datasets that capture the full relationship between load and wind, it provides the best assessment of wind's capacity value (Keane et al. 2011). Approximation methods must therefore be justified on grounds of ease of coding or lack of data. A brief summary of approximation methods is also given below.

4.2 Recommended ELCC Method

The Institute of Electrical and Electronics Engineers (IEEE) Wind and Solar Power Coordinating Committee's Wind Capacity Value Task Force has come up with a preferred methodology to calculate capacity value of wind power (Keane et al. 2010):

1. Conventional generation units are modelled by their respective capacities and forced outage rates (FOR). Each generator capacity and FOR is convolved via an iterative

method to produce the analytical reliability model (capacity outage probability table (COPT)) of the power system. The COPT is a table of capacity levels and their associated probabilities (Billinton and Allan 1996). The cumulative probabilities give the LOLP for each possible available generation state. Run-of-river hydro is usually treated by its time series. Usually decades of data of how run-of-river hydro generates during peak loads is available.

2. The COPT of the power system is used in conjunction with the hourly demand time series to compute the LOLE without the presence of wind generation.
3. Wind power cannot be adequately modelled by its capacity and FOR because wind availability is more a matter of resource availability than the plant availability. Time series for the wind power output is treated as negative load and combined with the load time series, resulting in a load time series net of wind power. In the same manner as above, the LOLE is calculated. It will now be lower (and therefore better) than the original LOLE.
4. The load data is then increased across all hours using an iterative process, with the LOLE recalculated at each step until the original LOLE is reached. The increase in the load is the ELCC, or capacity value, of the wind generation.

4.2.1 Approximation Methods

An alternative risk calculation to the preferred method is the multi-state approach, which utilises a probabilistic representation of the wind plant (d'Annunzio and Santoso 2008). Similar to conventional units with de-rated states, the wind plant is modelled with partial capacity outage states, each of which has an associated probability. To evaluate the LOLP at a given time, the wind generation is included in a COPT calculation in the same manner as a multi-state conventional unit. The ELCC calculation then proceeds as described in the preferred method, except using the modified calculation.

Garver proposed a simplified, approximate graphical approach to calculating the ELCC of an additional generator (Garver 1966). This has been an important method but has been superseded by advances in computing power.

Loss of load probability at time of annual peak demand is used as a proxy for system risk in some regions (National Grid UK, 2004). Probability distributions are required for the demand and available wind capacity at time of annual peak (the distribution for available conventional capacity is derived via a capacity outage probability calculation, as in the ELCC calculation method) (Aguirre et al. 2009). The main criticisms of an annual peak calculation are that it does not explicitly consider loss of load at other times of the year, and that it is difficult to obtain appropriate probability distributions for the wind resource at annual peak, and also for the peak load.

There has been considerable interest in using capacity factors (average output) calculated over suitable peak periods to estimate the capacity value of wind. Some of these approximations are reasonably accurate (Milligan and Porter 2008). Although capacity factor approximations may be useful as quick screening methods (for instance, a higher capacity factor would usually imply a higher capacity value on the same system), they do not capture the short term or annual variability of wind power, or the correlation of wind availability with demand.

The z-statistic method (Dragoon and Dvortsov 2006) is based on taking the difference between available resources and load over peak demand hours (surplus availability) as a random variable with an associated probability distribution. The z-statistic for that distribution (mean divided by standard deviation) is taken as the primary system adequacy metric. The incremental load carrying capability for an added power plant is taken to be the load addition that keeps the z-statistic constant.

A Monte-Carlo simulation approach with varying load, wind and hydro levels and outages is somewhat similar than the recommended method regarding COPT. However, to model the auto- and cross correlations of wind and load is not straightforward and real data preserves the underlying correlations in a more correct way.

It is essential to consider the utilization time when one compares the capacity value of wind power with, e.g., a base loaded unit. To get, e.g., 100 GWh/year one needs about 40 MW of wind power (utilization time 2500h) or 15 MW of coal power (utilization time 6700h). If wind power has a capacity value of 25% then this means 10 MW which corresponds to 67% capacity credit of the coal power plant. So one should compare the capacity credits in MW for the same yearly energy production and not the percentage values.

4.3 Checklist: Capacity Value

Checklist of Key Issues: Capacity Value

- Gather chronological synchronised wind and load data that captures the correlation with wind and load data. This is of paramount importance, and the robustness of the calculations is highly dependent on the volume of data collected. Data on generation unit installed capacity and forced outage rates is also required.
- Approximations should be avoided where possible, and a full net load ELCC calculation is the preferred method.
- The preferred ELCC calculation includes the following:
    - Convolving generator capacity and forced outage to produce the COPT of the power system, a table of capacity levels and their associated probabilities.
    - LOLE for each hourly demand level is calculated from the COPT table, first without the presence of wind generation. Wind is added as negative load, and load is increased until the same LOLE is reached as would be the case without wind power.
- Insufficient data can necessitate the usage of approximation methods, which can provide useful insight. However, the limitations of such should be recognised.

References

Aguirre, P.E.O.; Dent, C.J.; Harrison, G.P.; Bialek, J.W. (2009). “Realistic Calculation of Wind Generation Capacity Credits.” *2009 CIGRE/IEEE PES Joint Symposium, Integration of Wide-Scale Renewable Resources into the Power Delivery System*, 29–31 July, Calgary, Alta., Canada.

Billinton, R.; Allan, R. (1996). *Reliability Evaluation of Power Systems*, 2nd ed. New York: Plenum.

Clark, K.; Jordan, G.A.; Miller, N.W.; Piwko, R.J. (2005). “The Effects of Integrating Wind Power on Transmission System Planning, Reliability and Operations.” New York State Energy Research and Development Authority technical report. Albany: NYSERDA.

d'Annunzio, C.; Santoso, S. (2008). "Noniterative Method to Approximate the Effective Load Carrying Capability of a Wind Plant." *IEEE Transactions on Energy Conversion* (23:2); pp. 544–550.

Dragoon, K.; Dvortsov, V. (2006). "Z-Method for Power System Resource Adequacy Applications." *IEEE Transactions on Power Systems* (21:2); pp. 982–988.

Garver, L.L. (1966). "Effective Load Carrying Capability of Generating Units." *IEEE Transactions on Power Apparatus and Systems* (85:8); pp. 910– 919.

Hasche, B.; Keane, A.; O'Malley, M. (2011). "Capacity Value of Wind Power, Calculation and Data Requirements: The Irish Power System Case." *IEEE Transactions on Power Systems* (26:1); pp. 420–430.

Holttinen, H.; Meibom, P.; Orths, A.; van Hulle, F.; Lange, B.; O'Malley, M.; Pierik, J.; Ummels, B.; Tande, J.; Estanqueiro, A.; Matos, M.; Gomez, E.; Söder, L.; Strbac, G.; Shakoor, A.; Ricardo, J.; Smith, J.C.; Milligan, M.; Ela, E. (2009). *Design and Operation of Power Systems with Large Amounts of Wind Power*. Final report, Phase one 2006–2008, IEA Wind Task 25, VTT Research Notes 2493. Available at http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf.

Keane, A.; M. Milligan; C.J. Dent; B. Hasche; C. D'Annunzio; K. Dragoon; H. Holttinen; N. Samaan; L. Söder; M. O'Malley. (2011) "Capacity value of wind power." *IEEE Transaction on Power Systems*, vol. 26(2), pp. 564-572.

Milligan, M.; Porter, K. (2008). "Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation." *WindPower 2008*, 1–4 June, Houston, Texas, United States. Available at http://amherstislandwindinfo.com/aiw-docs/milligan-nrel-wind-capacity-value.pdf.

National Grid UK. (2004). "GB Security and Quality of Supply Standard Issue." Available at http://www.nationalgrid.com/NR/rdonlyres/FBB211AF-D4AA-45D0-9224-7BB87DE366C1/15460/GB_SQSS_V1.pdf.

NERC (North American Electric Reliability Corporation). (2009). "Special Report: Accommodating High Levels of Variable Generation." Princeton, NJ: NERC www.nerc.com.

5 Production Cost Simulations and Flexibility Assessment

Jody Dillon, Mark O'Malley, Juha Kiviluoma, Hannele Holttinen, Michael Milligan

This section describes in detail the Production Cost Simulation and Flexibility Assessment box (Figure 13 red circle) in the wind integration study components flow chart.

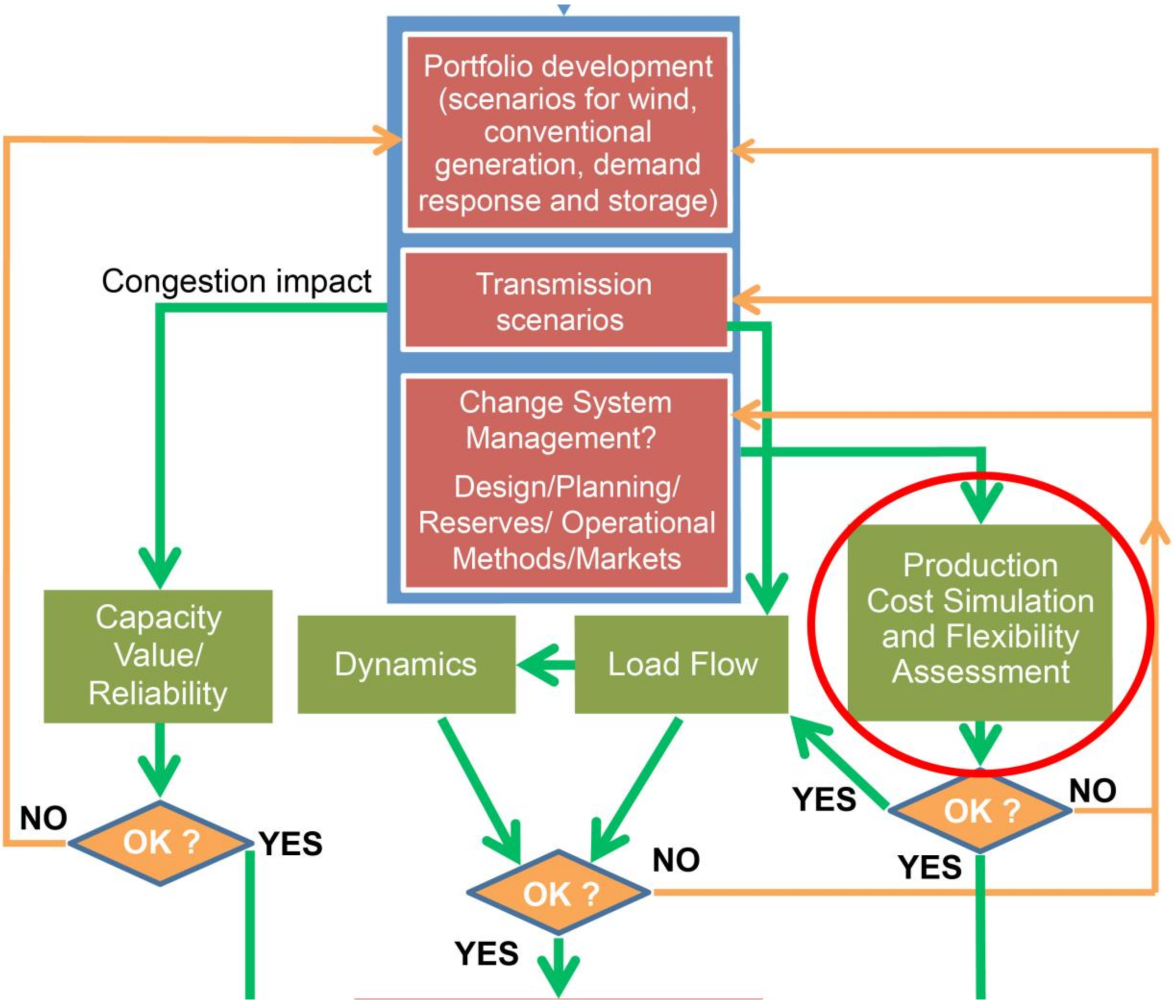


Figure 13. Wind integration study components: production cost simulations and flexibility assessment

The section will start with discussion of flexibility assessment, which is emerging as an important step in integration studies for higher penetration levels of wind power. Then important issues in production cost simulation (UCED modelling) with wind power are described.

5.1 Production Cost Simulation

Production cost simulation is the main study vehicle used to assess the impacts of wind power integration on flexibility, operating costs, and emissions. It involves optimising the scheduling of load and generation resources to meet expected demand over various time frames with consideration of cost and constraints (system, physical, and operational) and expected wind power. Production cost simulation is comprised of UCED, to simulate optimal short-term energy balance in the power system. The analysis may be extended to the time scale of automatic generation control (Ela and O'Malley 2012). Usually several different model runs are made in order to evaluate the costs and benefits of wind power as well as other options for power generation (see Section 7.1 for a more complete discussion).

In a fully developed model, the constraints in the optimisation ensure the physical feasibility of the short-term operational plans and reliability under uncertainty. The committed units need to be able to manage frequency control with reserve allocation, as well as meet the ramp requirements over all time frames. To assess the true capacity of the system to respond to change, the limitations and constraints of the system must be accurately modelled. Otherwise, a higher level of flexibility than exists in reality is assumed and the true impact of wind power is not captured. On the other hand, the analysis should consider what new sources of flexibility are possible in the timeframe of the study.

The variability of wind power generation should be representative of the expected variation in the study time frame. Time series based on wind speed measurements or meteorological models do not usually capture the variability correctly. There is usually at least some correlation between wind and load and therefore the time series should be synchronous. Catching wind power impacts usually requires simulations at high enough temporal resolution. Hourly time scale is often considered detailed enough, but 10–15-minute time steps will catch more ramping constraints experienced by conventional power plants. Characteristic variability of wind power and loads from several different power systems has been documented in Holttinen et al. (2011).

Wind power also introduces additional uncertainty, which needs to be considered. At higher wind penetration levels, the day-ahead uncertainty from wind power will get larger than uncertainty from loads. Typical wind power day-ahead and hour-ahead uncertainties have been documented in Hodge et al. (2012). For load forecasting, the accuracy does not improve that much with decreasing time horizon. How the uncertainty in the wind plant output forecast is handled with respect to the load forecast uncertainty is important.

Thus, with increasing levels of wind energy, it is important to capture more detail and the current constrained optimisation paradigm may need to be adapted (Kiviluoma et al. 2012; Dragoon and Milligan 2003). Possible adaptations include the following:

- Changing the rules
    - Commitment/spot market frequency
    - Liquid intra-day markets and regulation markets
    - Dynamic reserve procurement
    - Stochastic unit commitment with dynamic reserve
    - Higher resolution UCED (e.g., 15 minutes instead of hourly)
    - Market and reserve rules optimised for higher wind
    - Complex bids (e.g., block bids, ramp limits)
    - Coupled optimisation of energy and transmission
    - Larger balancing areas
- Technologies
    - Better wind power forecasts
    - Wind power curtailment, when there are no other more cost effective ways for flexibility
    - Increasing available transmission by controlling power flows (FACTS, etc.)
    - More transmission lines
    - Flexible thermal power plants
    - More power capacity in reservoir hydro power
    - More pumped hydro, compressed air energy storage, other electrical storage
    - Demand flexibility/Price sensitive demand

- Electrification of heating, cooling, and transport with flexibility measures

One issue is including ramping requirements with larger wind penetration levels—is there enough capacity to move the operational point of power plants fast enough when the ramps get steeper at higher wind power penetrations? The optimisation of simultaneous ramping of multiple units is required to ensure this. It can lead to situations where fast units are used to help slower but less expensive units to reach required production levels during a ramp event. A realistic representation of these events requires time resolution of some minutes.

Table 3 details how the rules may need to be changed at some point when the share of wind power grows. Therefore, the models used for the analysis should also take these evolutions into account, if applicable, for the study footprint in the future situation to be analysed.

Table 3. Evolutions for short-term energy balance with increasing wind energy penetrations (Kiviluoma et al. 2012).

		Scheduling Frequency	
	Explanation	**Once per Day**	**More Regular Scheduling**
Dynamic Reserve Procurement	A reserve requirement that is based on dynamic forecast error estimates at different time horizons	Wind power increases tertiary reserve significantly, but the impact will be more limited when the forecast uncertainty is accounted for dynamically	The combined impact of more regular UC and dynamic reserve procurement would help to keep tertiary reserve requirement relatively low most of the time
Stochastic UC	Optimisation of UC decisions over several scenarios for possible outcomes of wind and demand	Improves the reliability and yields more optimal UC.	Reduces tertiary reserve procurement and improves UC optimality further
Scheduling Resolution	Scheduling period is shortened (e.g., from hourly to 5 minutes)	Ramps within the scheduling period will be smaller, which reduces regulating reserves; scheduling accuracy will be improved	

The recent trend in wind integration studies has been towards simulating larger areas. This is due to the fact that most impacts of wind power can be diminished by using transmission capacity to neighbouring countries or areas. It is also the trend in electricity markets to include several countries and subsystems. To capture the impacts better, simulation of regions containing all relevant neighbouring areas or the whole market area is needed. Interconnection possibilities with the flexibility from neighbouring areas is an important assumption influencing the results (see Chapter 2 Input Data).

Grid congestion (power flows) is not always included in the UC models, as the network calculations have been computationally too time consuming. Inclusion of grid congestion becomes increasingly difficult when the system size increases or stochastic UC is used. Unfortunately, optimising wind power UC would benefit or even require those approaches. As an approximation, the scheduling problem for larger areas can be divided into multi-area tasks, with set transmission limits between the areas. In this case, using thermal capacities of lines would give too optimistic results because all this capacity is not always available in system operation. A better assumption is to use net transfer capacities defined by the TSOs. Iterative solutions could also be used.

Data for thermal plants should be detailed enough to capture variable O&M costs and flexibility costs (including heat rate curves, start-up costs, wear and tear costs of ramps and start-ups, and emission costs) and constraints (including run-up rates, ramp rates, and minimum load factors) and system (ancillary) service capabilities for frequency control. UC models use mixed integer programming to capture the non-linear behaviour or starts and stops of individual units. The impact is influential at higher penetration levels (Shortt et al. 2013). However, for larger, interconnected areas linear programming has been introduced to reduce the problem size. This more simplified linear programming needs still to be developed to include at least some implications of start-up costs, minimum load factor, and lead times. It is also of importance to compare the two methods.

Hydropower with reservoirs can offer a lot of flexibility to the system. However, these systems often have constraints regarding river flows and coupling of power plants along the river. Detailed modelling of hydropower is needed to capture the river basin flows in a consistent way. In some systems like in the United States, there is flexibility in the hydro system that would be physically available to help with balancing that is not made available to the model.

Mitigating the impacts of wind power can include flexible demand and energy storages. There are at least two kinds of demand response to be incorporated in the UC models: shaving the demand (cutting) and shifting the demand to other point in time. Demand shifting has similar restrictions on electricity storage, since the amount of energy that can be shifted is usually limited. Furthermore, there are time limits on how long the demand can be reduced before the same energy has to be restored. Electricity storage can have longer time limits and this raises the need to integrate day-ahead perspective with a longer-term horizon in order to value to storage contents properly.

One issue is including ramping requirements with larger wind penetration levels. Is there enough capacity to move the operational point of power plants fast enough when the ramps get steeper at higher wind power penetrations? The optimisation of simultaneous ramping of multiple units is required to ensure this. It can lead to situations where fast units are used to help slower but less expensive units to reach required production levels during a ramp event. Realistic representation of these events requires time resolution of some minutes.

Recommendations for production cost estimations:

1. Synchronous multi-year time series of wind and load with high enough temporal resolution (at least hourly, preferably better especially if ramps are an issue)—the time series should capture the smoothing of large-scale wind power and representative for real wind power variations.
2. Realistic assumptions should be made about the operating rules and regulations in the study time frame (considering frequency and temporal resolution of markets, dynamic reserve procurement, as well as sharing of balancing resources across balancing areas).
3. With higher wind penetrations, it is important to model the impact of uncertainty on dispatch decisions in UCED; for example, using a stochastic optimisation and rolling planning method (Tuohy et al. 2009).
4. Increased operating reserve targets should be estimated using wind and load forecast uncertainty—with higher wind penetrations, use of dynamic reserves, faster markets, and increased market resolution is recommended.
5. To assess the true capacity of the system to respond to change, the limitations and constraints of the system must be accurately modelled. This includes inflexibilities of conventional plants, such as minimum generation levels, ramp rates, minimum up/down

times, start times, load times, and for hydropower plants, the degree of freedom to control power production considering river flow constraints. To capture these limitations, it may be necessary to use mixed integer programming. For large systems or for very high-level studies, linear programming approximations may suffice if underestimation of costs and overestimation of flexibility is quantified via a suitable benchmarking exercise.

6. To accurately model the limitations of interconnections with neighbouring regions, the neighbouring system should be explicitly modelled , including also the wind power installed there (Such as with the European Network of Transmission System Operators for Electricity [ENTSO-E] Ten-Year Network Development Plan 2012 [TYNDP]). Alternative approaches include assuming full availability of interconnectors or to assume fixed flows obtained from other studies or based on assumed market prices in neighbouring regions. These approaches will err on the optimistic and pessimistic sides, respectively (ENTSO-E TYNDP 2012), and this should be mentioned clearly in the study conclusions.
7. To capture the limitations from the transmission network, it is important to consider congestion and N-1 security within UCED (the system should always operate in a state where any single largest failure, N-1, could happen without risking security). To reduce the computational burden for large systems or where stochastic optimisation is used, net transfer capacity, or iterative methods can be used. In systems with very high levels of renewable generation, it may be also necessary to model additional stability constraints arising from the studies described in Section 6.2 Dynamic Stability Analysis.
8. In systems with significant amounts of hydropower, it is essential to consider different hydrological scenarios.
9. Depending on the study horizon and levels of wind penetration, the possibilities from new sources of flexibility should be analysed, if applicable (heating, cooling, electric vehicles, storages, demand response, dynamic line rating).
10. Study results and conclusions are particularly sensitive to the non-wind case used as a basis for comparison and assumptions regarding the types of generation that wind power will displace, especially if estimating integration costs. Using a scenario with equivalent wind energy but with a perfectly flat profile may result in impacts not entirely related to wind energy (Milligan et al. 2010). The use of generation planning models to ensure consistent scenarios should be considered.

5.2 Flexibility Assessment

Flexibility can be described as the ability of the power system to respond to change in different time scales. The capability to respond to changes is limited by physical constraints on generation resources and of the power system in general. Thus, flexibility can also be understood as the absence of constraints on the system.

For wind power integration, flexibility is required to manage the resulting variability and uncertainty to ensure that demand balance, security, and reliability constraints are met. Typical sources of flexibility include conventional generation, which can be dispatched up and down. Wind power can also be a source of flexibility. However, as this requires energy to be held back to enable reserve and/or frequency response, this may be an expensive source. Transmission allows for the sharing of flexibility between interconnected regions. Load is increasingly used to provide a degree of flexibility in the form of load shifting and load shaving. Storage is a valuable source of flexibility but with comparatively high capital costs for new installations.

Flexibility needs can be divided into planning and operational horizon flexibility. Planning horizon is focused on how to determine the future need for flexibility and how to get it—it is the need for new build up or make market design so as to incentivise all flexibility to be used by the system needs. Operating horizon is focused on how to best use the flexibility that is available from installed generation/storage/demand side. That will include UC and possibly some form of stochastic UC in order to minimise the risk of getting caught short.

So far, flexibility assessment in the operating horizon is generally conducted implicitly within production cost simulations. Production cost simulation is comprised of UCED. Various methods have been proposed to assess the adequacy of power systems and develop adequacy metrics with respect to their flexibility. Lannoye et al. (2012) describes a ramping resource expectation metric for use in power system planning studies. Broader system flexibility metrics are also proposed, which consider a wide range of power system characteristics that can be used to quantify the inherent flexibility in power systems (IEA 2011). These methods are evolving and may become more important in systems with high levels of wind penetration.

For planning time frame, there will be a need for generation expansion-type models that can help screen alternative generation mixes to see if they are flexible enough in future high penetration levels of wind power.

For studying larger penetrations of wind power, any integration study should develop a scope that acknowledges and/or includes new potential sources of flexibility. In some cases, the existing flexibility that can be obtained from some combination of markets and flexible technologies may already exist. However, a robust wind integration study can assess the existing flexibility and provide indicators of whether additional flexibility may be economic, and the time scales and other properties that the reserve stack must provide to efficiently integrate the level of wind energy studied.

5.3 Checklist: Production Cost Simulations and Flexibility Assessment

Checklist of Key Issues: Production Cost Simulations and Flexibility Assessment

- Synchronous input data for wind and load with at least hourly resolution and one year is required. Multiple years would be preferable. Capturing the smoothed out variability of wind power production time series for the geographic diversity assumed is important. It is important to use wind forecasting best practices for the uncertainty of wind power production, assumed for the year of study, with possibilities to update forecasts closer to delivery hour.
- Capture system characteristics and response through operational simulations and UCED.
- Model the flexibility options, as well as any constraints of flexibility. This includes generation unit ramping, start/stop limitations, cycling impacts, and associated costs, as well as hydrological constraints in case of hydropower. Take into account the operational practices that may enable or limit flexibility to be used. Synchronous data for run of the river hydro also becomes critical for hydro dominated systems.
- Take into account the possibilities of flexibility that exist in neighbouring regions. To accurately model the limitations of interconnections, the neighbouring system should be explicitly modelled, including also the wind power installed there. Alternative approaches include assuming full availability of interconnectors or to assume fixed flows obtained from other studies or based on assumed market prices in neighbouring regions. These approaches will err on the optimistic and pessimistic sides, respectively, and should be mentioned clearly in the study conclusions.
- To capture the limitations from the transmission network, it is important to consider congestion and N-1 security within UCED. To reduce the computational burden for large systems or where stochastic optimisation is used, net transfer capacity, or iterative methods can be used. In systems with very high levels of renewable generation, it may be also necessary to model additional stability constraints arising from the studies described in Section 6.2.
- Study results and conclusions are particularly sensitive to the non-wind case used as a basis for comparison and assumptions regarding the types of generation that wind power will displace, especially if estimating integration costs. Just adding wind power, or using a scenario with equivalent wind energy, but with a perfectly flat profile, may result in impacts not entirely related to wind energy. The use of generation planning models to ensure consistent scenarios should be considered.
- Assess the existing flexibility and provide indicators of whether additional flexibility may be economic, and the time scales and other properties that the power plants must provide to efficiently integrate the level of wind energy studied. We recommend that for higher wind penetration levels, a scope that acknowledges and/or includes new potential sources of flexibility be made.

References

Dragoon, K.; Milligan, M. (2003). "Assessing Wind Integration Costs with Dispatch Models: A Case Study of PacifiCorp." In *Proceedings of WINDPOWER 2003*, 18–21 May, Austin, Texas, United States.

Ela, E.; O'Malley, M. (2012). "Studying the Variability and Uncertainty Impacts of Variable Generation at Multiple Timescales." *IEEE Transactions on Power Systems* (27:3); pp. 1324–1333.

ENTSO-E (European Network of Transmission System Operators for Electricity). (2012). *Ten-Year Network Development Plan 2012* (TYNDP 2012 Package). Includes six Regional Investment Plans, one Ten-Year-Network-Development Plan, and one Scenario Outlook and Adequacy Forecast. Available at https://www.entsoe.eu/system-development/tyndp/tyndp-2012/.

Hodge, B-M; D. Lew; M. Milligan; H. Holttinen; S. Sillanpää; E. Gómez-Lázaro; R. Scharff; L. Söder; X. G. Larsén; G. Giebel; D. Flynn; J. Dobschinski. (2012). "Wind Power Forecasting Error Distributions, an International Comparison." *11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems* as well as on Transmission Networks for Offshore Wind Power Plants Conference, Lisbon, Portugal.

Holttinen, H.; Kiviluoma, J.; Estanqueiro, A.; Gómez-Lázaro, E.; Rawn, B.; Dobschinski, J.; Meibom, P.; Lannoye, E.; Aigner, T.; Wan, Y.-H.; Milligan, M. (2011). "Variability of Load and Net Load in Case of Large Scale Distributed Wind Power." In *Proceedings of 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 25–26 October, Århus, Denmark.

IEA (International Energy Agency). (2011). Harnessing Variable Renewables. A Guide to the Balancing Challenge available at http://iea.org/publications/freepublications/publication/Harnessing_Variable_Renewables2011.pdf

Kiviluoma, J.; Meibom, P.; Tuohy, A.; Troy, N.; Milligan, M.; Lange, B.; Gibescu, M.; O'Malley, M. (2012). "Short-Term Energy Balancing With Increasing Levels of Wind Energy." *IEEE Transactions on Sustainable Energy* (3:4); pp. 769–776.

Lannoye, E.; Flynn, D.; O'Malley, M. (2012). "Evaluation of Power System Flexibility." *IEEE Transactions on Power Systems* (27:2); pp. 922–931.

Milligan, M.; Ela, E.; Lew, D.; Corbus, D.; Wan, Y. (2010). "Advancing Wind Integration Study Methodologies: Implications of Higher Levels of Wind." Presented at *WindPower 2010,* 23–26 May, Dallas, Texas, United States.

Shortt, A.; O'Malley, M.; Kiviluoma, J. (2013). "Accommodating Variability in Generation Planning." *IEEE Transactions on Power Systems* (28:1); pp. 158–169.

Tuohy, A. and Chandler, H. (2011). "Flexibility Assessment Tool: IEA Grid Integration of Variable Renewables Project." *2011 IEEE Power and Energy Society General Meeting*, 24–29 July, Knoxville, Tennessee, United States.

Tuohy, A.; Meibom, P.; Denny, E.; O'Malley M. (2009). "Unit Commitment for Systems with Significant Wind Penetration." *IEEE Transactions on Power Systems* 24(2); pp. 592–601.

6 Transmission Grid Simulations: Load Flow and Dynamics

Damian Flynn, Hans Abildgaard, Frans vanHulle, Ana Ciupuliga, Atle Rygg Årdal, Ana Estanqueiro, J Charles Smith, Antje Orths, Enrico Maria Carlini, Mark O'Malley, Hannele Holttinen

This section covers the simulation boxes regarding the transmission grid (Figure 14 red circle) in the wind integration study components flow chart.

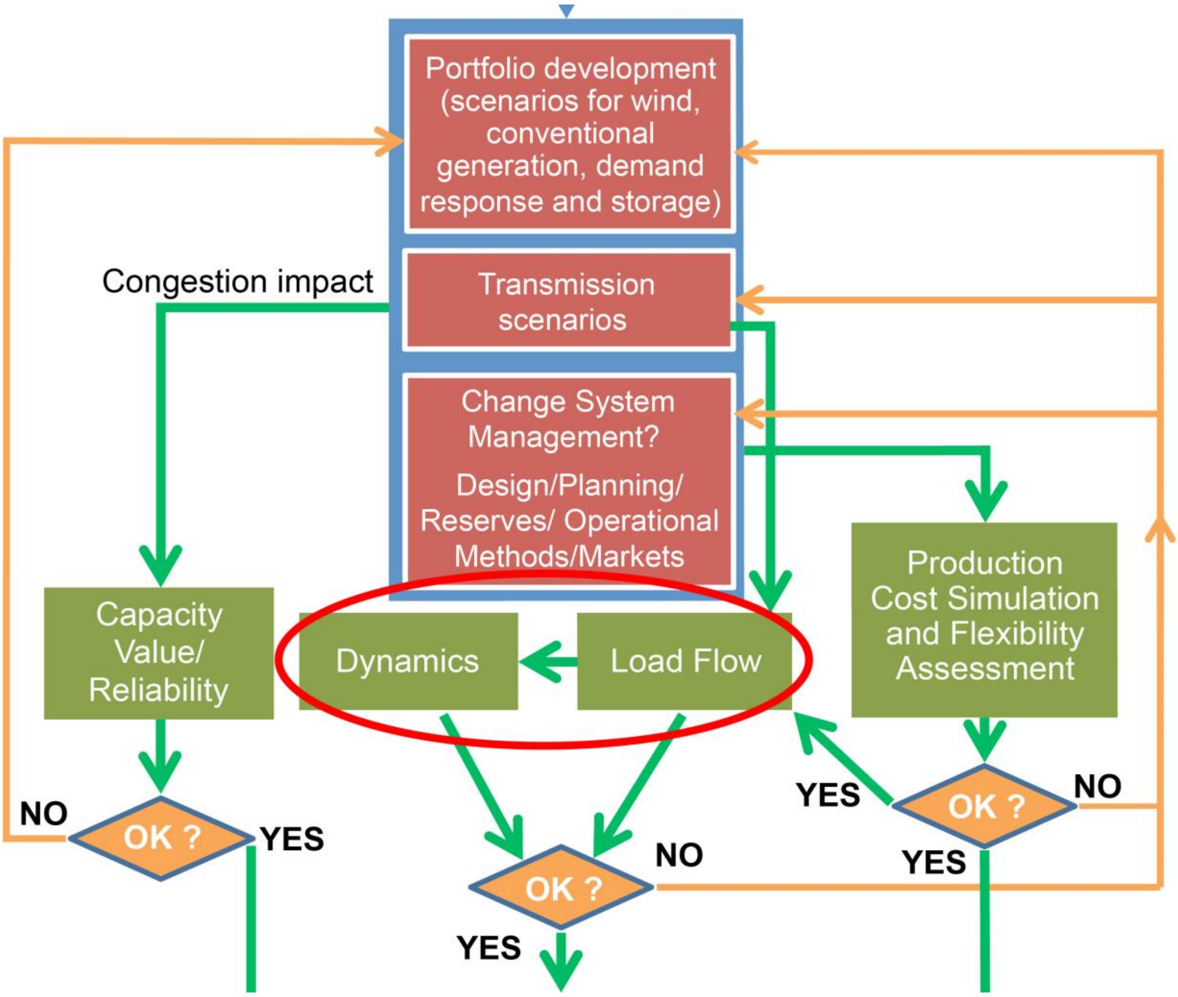


Figure 14. Wind integration study components: transmission scenarios, load flow and dynamics

Once production cost simulations have indicated that a given wind integration scenario is feasible, steady-state load flow; N-1 contingency analyses; and, often, dynamic system stability analyses are performed. These simulations confirm the steady-state adequacy and use of the transmission system and assess if the plant portfolio and grid are strong enough to cope with both temporary disturbances and significant failures. The chosen deployment of wind generation (including different wind turbine technologies and wind distributions) can also be evaluated against existing grid code requirements. Different mitigation or participation options can also be considered. The need to assess impacts on power system dynamic stability will be important especially with higher penetration levels of wind power.

Load flow and dynamic simulations can also be thought of giving inputs to the production cost simulation, this is reflected in the transmission scenarios of portfolio development and this can be an iterative process. If the load flow and dynamic simulations reveal deficiencies, the grid must be reinforced. This is the iteration loop to the portfolio setup regarding transmission scenario. Similar simulations are conducted as part of transmission planning where objectives include relieving existing congestions, arbitrage between markets, and maintaining (or improving) security of supply (transmission adequacy). A host of system conditions must be analysed as part of a transmission expansion plan.

6.1 Load Flow Simulations

To assess the impacts of wind power on the transmission grid, network contingency situations are studied to meet the criteria of power system operation and safety established by the system operator. This involves steady-state load flow analyses; system reliability analyses through probabilistic methods; and, often, dynamic system stability analyses.

The steps of load flow simulations are as follows:

- Establish the baseline case and study scenario: Create a number of credible load flow and stability base cases that represent high penetration of wind (and solar) generation expected. These cases can be deliberately selected with the expectation that they would represent some of the most challenging conditions for the system. Often the snapshots chosen include high-load and low-load situations. However, high wind plant output during shoulder periods may create new transmission system loading patterns and lead to high stress periods on the transmission system, which had not been previously experienced and now needs to be analysed. Wind power means adding more situations to be studied than just some snapshots, preferably a high number of cases to represent possible wind and load situations. The high-wind situations are compared with low-wind or no-wind situations. Operating conditions with a large number of synchronous generators displaced by variable renewable energy resources are relevant.
- Connection substations for wind power injection. At the snapshot of time represented in these cases, the injection of wind power is simulated in the nearby substations with chosen capacity factors for windy and non-windy situations. At this stage, the selection of the candidate connection substations is carried out.
- Deterministic steady-state security analysis. Load flow analyses shall be performed to check possible bottlenecks (congestion) in the transmission network and to assess the system's capacity to control the voltage profile. When bottlenecks are set by thermal stability, then this kind of analysis is enough, otherwise dynamic studies are needed. The effect of wind energy productions on the voltage profile differs according to the type of wind energy units (e.g., asynchronous generators, double fed asynchronous generators, synchronous generators connected via converters). Therefore, depending on the assumed turbine technology and the connection rules, an appropriate level of reactive power Q absorption/production shall be simulated to determine the need for means of reactive compensation and to test the conformity of the voltage profiles to the N and N-1 security criteria. At this level, a first screening on transmission bottlenecks caused by the additional wind generation is carried out, although the final decision on the optimal network reinforcements is taken after a more comprehensive probabilistic analysis (see below).
- Short-circuit levels: Short-circuit analysis may be performed to assess the ability of the network to adjust the voltage, with specific reference to rapid voltage changes. Short-circuit power ratio calculated at each bus highlights the "stiffness" of the power system regarding power quality supply (namely voltage quality). Short-circuit levels in the network are simulated both before and after the addition of wind power. At high wind penetration situations, synchronous generation will not be dispatched, which may lead to

a reduction in the minimum short-circuit level and a reduced short circuit ratio. This, in turn, may affect the power quality, voltage step changes after shunt switching and the operation of line commutated HVDC converters and wind turbine power electronic controls. The impact of the short-circuit currents on the operation of the protective relay system should also be investigated. Due to the reduction in short-circuit levels, it is unlikely that the change in short-circuit current will have any impact on the momentary or interrupting duty on the circuit breakers.

- Power system recovery: Power system recovery after a disturbance is studied by simulating the impact of failures. Impact of failures at critical places, or nodes near wind power plants are studied, or sometimes the largest possible failure (N-1 criterion), and two largest failures (N-2 criterion) are used. Simulations are carried out, for example, during 20 seconds from the occurrence of a three-phase fault. The voltage recovery and how wind power penetration affects the power system have been studied (Smith et al. 2010).

6.2 Dynamic Stability Analyses

Damian Flynn, Barry Rawn, Hans Abildgaard, Antje Orths, Enrico Maria Carlini

The need to assess the impacts of wind generation on power system dynamics will be important at higher penetration levels.

For the execution of dynamic analyses, inputs from the transmission system structure (including the already selected reinforcements) and from the UCED are needed. Stability studies will require much greater detail of the generating units than UCED simulations. UCED will provide steady-state snapshots of the power system for varying demand levels and wind generation patterns. Such analyses should already recognise a range of dynamic issues (e.g., ramping capabilities of committed units, spinning reserve requirements, local network constraints). Iterations loop back to transmission enhancement since one of the outcomes of dynamic analyses might also suggest a review of the selected transmission reinforcements (e.g., to ensure a critical clearing time above predefined thresholds to warrant system stability).

Subject to particular system concerns, system dynamics studies can address the following:

- *Transient stability (i.e., angle stability):* ability to maintain generator synchronism when subjected to a severe transient disturbance
- *Small-signal (oscillatory) stability:* ability to maintain a steady-state condition on voltage, current, and power magnitudes after having been subjected to a small disturbance; here the system frequency and synchronism are not an issue
- *Frequency stability:* ability to maintain system frequency following a major imbalance between generation and load
- *Voltage stability:* ability to maintain an acceptable voltage profile after being subjected to a disturbance

With appropriate dynamic data, studies can:

- determine if the grid is sufficiently strong to sustain both temporary disturbances and significant (dimensioning) contingencies, and capable of recovering satisfactorily from those events; and
- evaluate the chosen deployment of wind against existing grid code requirements, and consider different mitigation or participation options that the regulatory regime allows.
- assess the transmission limits when these are set by transient stability, small-signal stability and/or voltage stability.

The objective of the above analysis is to determine the optimal measures to avoid the risk of wind generation curtailment due to dynamic constraints, adopting “soft measures” (appropriate setting of the controllers, coordinated protection schemes) or “hard measures” (additional network reinforcements).

Dynamic studies have traditionally (not for wind integration) involved snapshot analysis of particular cases, where the periods of greatest system stress are well known (e.g., annual peak load). Depending on the correlation of diurnal/seasonal load patterns with wind generation output, periods of system stress may potentially occur over a much broader range of the year. A simplistic approach can consider system demand and wind generation as independent variables, which may limit the number of additional cases considered (e.g., demand high coupled with wind high), but the likelihood of occurrence of such scenarios is not great. Where possible, wind and demand time series should be employed, in order to capture the underlying correlation. Multi-year analysis should perhaps be involved in order to capture less common but threatening scenarios.

Dynamic analysis can be executed in the same expected operating conditions (peak and low load conditions) considered at the steady-state security stage, to ensure coherency, and taking into account the lack of correlation between wind generation and demand pattern. However, for each kind of simulation the relevant cases need to be identified, and different cases may be relevant for steady-state and dynamic calculations.

Of particular interest will be those periods of time when there is a high penetration of asynchronous generation, or when large exports of wind power occur across an area. Specific concerns to assess in higher penetration levels of wind are as follows:

- During periods of high wind penetration, with reduced numbers of conventional generators online, the frequency stability of the system may be affected by the reduction in governor response, and, particularly for smaller systems, the reduction in synchronous inertia.
- Periods of wind power export from one region to another may result in voltage angle differences across a synchronous area beyond typical levels and threaten angle stability, both from a small-signal (oscillatory) and transient stability point of view. Significant reverse power flow from former load feeders can also occur.
- Transient stability of critical synchronous generators may be reduced when other synchronous generators are de-committed and replaced with wind at medium- or low-voltage levels, behind a relatively large impedance.

Wind turbines can contribute to the needs of the power system for system restoration with fault-ride-through capabilities (Boemer, et al. 2011b).However, the level of support is network sensitive. The disconnection of wind turbines due to faults can amount to a large loss of active power infeed in some systems, making it important to accurately assess the extent of voltage depressions and threat to frequency stability. The effect of protection systems can thus play a crucial role, and its simulation may require more sophisticated calculation methods (van der Meer 2010). However, the converter controls of wind turbines complicate analyses of small signal (oscillatory) and voltage stability. This argues for the continued development and support of accurate and field-tested wind turbine models for use in dynamic stability programs.

Regarding input data, the dynamic characteristics of all generators and the load are required, as well as increased detail on the configuration and electrical parameters of the transmission and distribution networks (see more details in Chapter 2). The modelling complexity will depend on the nature of the analysis. Transient phenomena caused by fluctuating wind energy production can last up to a minute, or several minutes in certain cases. Therefore, considering the time scale of this phenomenon, dynamic models suited to long-term dynamics are needed.

Recommendations for configuring the dynamic simulations include the following:

- Ideally, studies should be performed with different wind turbine technologies, but often it is sufficient to utilise generic models that capture the minimum performance required in the connection code.
- Different wind penetration and demand levels shall be included to best understand the dynamic system limits.
- Frequency stability studies require the inertia, droop, and governor settings of all units to both simulate individual unit responses and the combined system response to major faults or contingencies, and to assess changes in frequency regulation capacity. A reduced network representation may be sufficient.
- Small-signal stability studies require an automatic voltage regulator (AVR), including power system stabiliser settings for synchronous generation.
- Transient stability analysis will require inertial values for synchronous generation, while the effect of protection devices for network and converter-interfaced generating equipment is also required. For example, boiler/steam turbine models would not be required for transient stability analysis (Miao et al. 2009).

The stability issues of concern for a particular system will depend on system size, wind distribution relative to the load and other generation, along with the UC and network configuration. They are likely to be first seen during the night or seasonal low-demand periods when instantaneous wind penetration may be high, even in cases where annual energy contribution is still not very high.

Variable-speed wind turbines decouple the rotating masses of the turbine from the electric grid, which offers a number of operational and quality benefits, but removes any intrinsic inertial capability. A reduction of inertia at times of high asynchronous penetration will alter the system response for both faults and contingencies, which can be particularly important for smaller power systems or those linked together by asynchronous HVDC links (Gautam et al. 2009). Low inertia has not, as yet, caused a problem for larger power systems but is being investigated (Eto et al. 2010; Vittal et al. 2010). Modern wind turbines can provide a synthetic response with its own characteristics that may be included as a study variant. Several studies based on meteorological or power measurement data (Brisebois and Aubut 2011; Rawn et al. 2010; Ruttledge and Flynn 2011; Miller et al. 2011) indicate that the aggregate supply of rotational energy at a national scale can assist the frequency response of the power system, but is not always available and changes with turbine operating point. For a smaller system like Ireland, mitigation measures for low inertia include disabling/replacing aspects of the standard distribution connected protection schemes for wind plants, as well as ensuring that conventional generators provide appropriate reserve in a timely manner following an energy imbalance. In addition, the capability of all generators to withstand high rates of frequency change will need to be reviewed. To mitigate dynamic stability problems, the use of fast-acting reactive power response devices during and following disturbances is required. This could be achieved by installing devices such as synchronous compensators, and/or requiring all wind plants and conventional generators to incorporate that specific capability.

Transient stability studies examine the operation of power systems during severe fault contingencies, with times of high wind penetration. Current grid code requirements regarding wind turbine fault behaviour are not a guarantee of transmission system stability, and proper representation of the impedance connecting the wind farms is crucial. It is important to evaluate the support actually delivered by wind turbines during grid faults, especially during reverse power flow situations where synchronous generators may have been de-committed to accommodate wind power. Critical clearing times can be studied to see whether they become shorter when wind power is connected at lower voltage levels, even if the turbines are equipped with grid-code compliant reactive current boosting (Boemer, et al. 2011b).

Additional considerations are as follows:

- Frequency fluctuations due to major faults in the power system (tripping of the most heavily loaded lines or largest generator infeeds) should be considered.
- Power fluctuations on the cross-border lines caused by variable production of the wind power plants should be examined to help to determine the margins for the cross-border transmission of power (net transfer capacity, also taking into account the production of wind energy).
- Network behaviour should be analysed in the event of faults, determining the voltage and frequency oscillation ranges, and stability margins in the event of major contingencies.
- Protection relay settings should recognise changes in the dynamic response of the system, and with any dynamic operating criteria (e.g. frequency variation range) adopted by the local TSO.
- The fraction of generation participating in governor control is a good metric for the expected frequency response of a system (Miller et al. 2011). The manoeuvrable capacity of such generation is also important with resources that provide significant incremental power for the frequency to return to its original working point.
- Reduced inertia at times of high non-synchronous penetration will alter the system response for both faults and contingencies, which can be particularly important for smaller power systems or those connected by HVDC links. Modern wind turbines can provide a synthetic response, but it is not always available and changes with turbine operating point (Ruttledge et al. 2012). Fast-acting load response or power injection from energy storage are also beneficial.
- Voltage stability is likely to be unaffected or enhanced by the presence of wind turbines (Knüppel et al. 2009), if their reactive power control capabilities are deployed to manage voltage (Vittal et al. 2010).
- To mitigate transient stability problems, fast-acting reactive power response devices during and following disturbances are required (e.g., installing FACTS, synchronous compensators, and/or requiring all wind plants and conventional generators to incorporate that specific capability). Wind power may also help damping oscillations.
- System stability studies should recognise that wind turbine controls, as part of a coordinated control strategy, may offer system advantages. Voltage Source Converter (VSC)-HVDC can to a certain extent also be used for system stabilisation (ENTSO-E 2011).

For offshore plants, the fast dynamics of DC grids make it necessary to incorporate and simulate detailed models on shorter time steps. In van der Meer et al. (2010), it was discussed how offshore wind power plants connected through VSC-HVDC can be accurately simulated in software packages that focus on the power system (electro-mechanical) dynamics of interest in the context of wind integration. With the proposed combined simulation strategy (stability simulation for the alternating current (AC)-grid dynamics, and electro-magnetic transient simulations for DC-grid dynamics) sufficient simulation speed and accuracy can be obtained.

Offshore wind power plants in DC grids can pose challenges also related to FRT. VSC-HVDC control strategies for offshore wind power plants comprising mixed wind turbine types can potentially prevent disconnection of VSC-HVDC connected wind power plants during onshore faults (van der Meer et al. 2009).

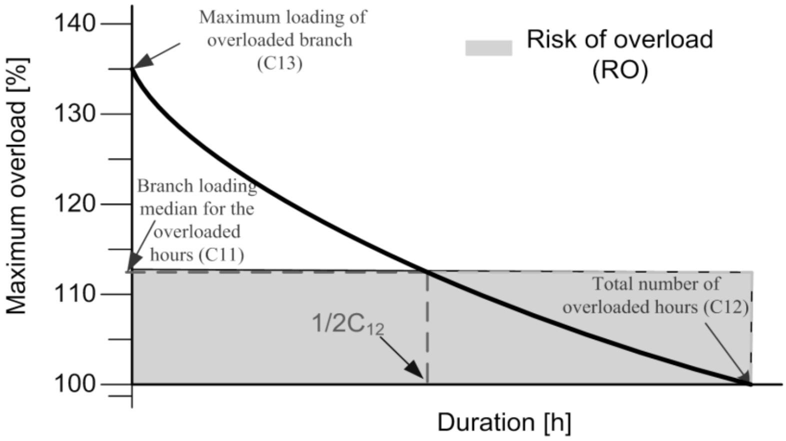
6.3 Network Reinforcements

Problems encountered in load flow or dynamic analyses can be solved by reinforcing the transmission grid. The amount of grid reinforcements needed is also one result of grid integration studies. The constraints of the underlying transmission network are also an important input to production cost simulations.

Because wind power brings net load situations that are different from more regular loads, probabilistic analyses is a recommended future option when deciding the best transmission grid reinforcements and associated investments – when availability of statistical data allows. Probabilistic analyses catch the uncertainty and variability during a year with many possible combinations of load, generation, and power exchange. They allow overcoming the limitations that a small subset of expected operational snapshots represent, and allow estimating possible congestion in the grid, in terms of duration and quantity, the yearly energy production of each wind power plant as well as the risk for the producer of being cut-off due to system constraints (i.e., risk of wind generation curtailment). Moreover, a probabilistic approach allows considering uncertainty factors such as the forced outage of transmission equipment, generation units, and the variability of wind generation. Through yearly based probabilistic simulations, one can identify the expected frequency of network overloads (hour/year) and the quantity of overloads (MWh/year). Market operation analysis for congestion purposes can also be made.

To justify transmission economically, the profitability of transmission reinforcements needs to be assessed. The benefit from the difference in the marginal generation cost between the interconnected areas (low-cost area and the high-priced area) has to be greater than the annual capital and operating cost of the transmission reinforcement. Also other criteria can be adopted like environmental benefits, in terms of carbon dioxide emission reduction, social benefits, in terms of enhancement of the "social welfare," variation of the system losses, etc. An example of criteria to assess the profitability of transmission reinforcements is presented in (ENTSO-E 2011), as well as indexes that are quantitatively evaluated with and without the new wind generation.

An example of a round-the-year approach by combining market simulations with static security analysis to deal with uncertainties is shown in Figure 15 where many combinations of load and generation using unit dispatch based on cost optimisation are created and analysed. For each combination, the branch loadings have been determined for normal and contingency situations. Criteria for prioritising bottlenecks were developed together with a method for ranking them according to a risk-based severity index. (Ciupuliga et al. 2012, see Figure 15). By analysing the risk of overload and the aggregated severity index, planners can decide whether bottlenecks are severe or if they can be solved (temporarily) via operational measures.



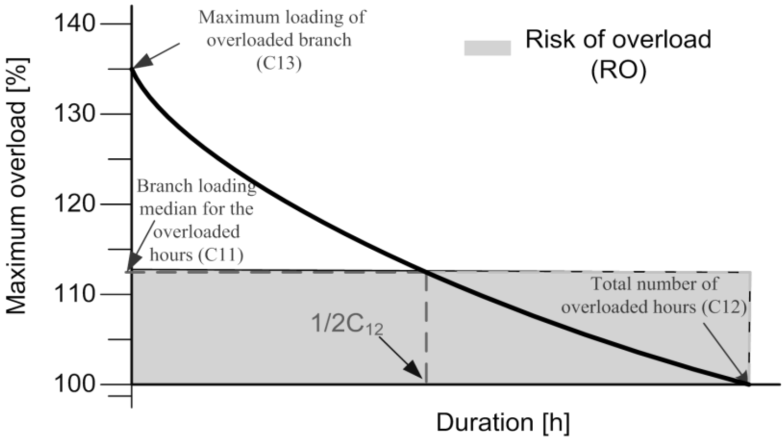


Figure 15. Maximum overload-duration curve for a branch during N-1, with highlighting of criteria and of risk of overload (Source: Ciupuliga et al. 2012).

Transmission capacity problems associated with wind power integration may be of concern for only a small fraction of the total operating time. In these cases, network investments can be avoided or postponed by maximising the full use of existing transmission lines: using online information (temperature, loads/dynamic line rating (DLR)), using FACTS devices to control the flow, and implementing high-temperature conductors to increase the transmission capacity of overhead lines. The potential net increase of transmission capacity through DLR can be significant in single cases (dena 2010). Replacing overhead cables with high-temperature conductors has still a higher effect but is also more expensive.

It is also important to note that grid reinforcements should be compared against the option of curtailing wind or altering operation of other generation in cases where grid adequacy is insufficient during only part of the time or for only some production and load situations. Coordination of hydropower and wind power in a region with limited export capability is another option to reduce the need for grid upgrade (Matevosyan 2006; Tande and Uhlen 2004). DSM that is controlled according to the wind and transmission situation is another option. The latter two may be more beneficial than limitation of wind power as energy dissipation is avoided.

These options can be regarded as taking the iteration loop back to changing operational practices and transmission grid inputs to the simulations. Despite application of wind generation controllability and DSM, grid expansion and/or capacity reinforcement may become necessary not only in cases of very high wind penetration but also when it is necessary to extend the grid to remote areas to collect important and proven wind resources.

Building the transmission network for the final amount of wind power has particular relevance in the case of offshore grid expansion planning. Offshore grids that interconnect several countries are associated with socioeconomic benefits because of increased trading opportunities between different market areas. They can also allow for connections to remotely locate offshore wind plants through future multi-terminal HVDC systems. The sum of these benefits should be compared with the investment cost of the grid. The grid configuration that yields the highest socioeconomic net benefit should be identified, in order to facilitate a coordinated planning process. Highest socioeconomic benefit is defined in this context as the lowest operational plus investment costs for the whole system considered. Offshore grid expansion planning is a task that requires complex modelling, including offshore grid configurations (3E, et al. 2011). The required external input includes detailed generation and grid data (capacity, costs, etc.) for the onshore grid, and offshore infrastructure cost data. A comparison between the benefit from direct connectors, tee-in connectors, or hub-to-hub connectors for the offshore transmission network is recommended.

6.4 Checklist: Transmission Grid Simulations: Load Flow and Dynamics

Checklist of Key Issues: Transmission Grid Simulations: Load Flow and Dynamics

- *Wind turbine models as input:* Appropriate model complexity will be dependent on study application. Validation of all models (conventional generators, wind turbine, and load) is important. Wind turbine models should be linked with (evolving) turbine technologies and grid code requirements in order to simulate wind turbine capabilities in a relevant way for the system in question.
- *Creating a number of credible load flow cases:* Wind power studies will need a wider range of analysis cases, not just traditional minimum/maximum load scenarios. An evaluation of the snapshot's statistical relevance would be beneficial.
- *Deterministic steady-state security analysis:* Load flow and short circuit analyses are performed to identify transmission network bottlenecks (congestion) to assess the system's ability to control the voltage profile and determine short-circuit current levels.
- *Network loading (congestion) assessment:* Network branch loadings should be determined for wind generation and load combinations, over a year, both for normal and contingency situations. Bottlenecks can be identified in a probabilistic manner if statistical data exists, analysing the overload risk and the severity.
- *Stability:* Different systems may have totally different dynamic issues (e.g., frequency stability, voltage stability, or transient stability challenges), implying that specific system studies may be required
- *Transient stability analysis:*
    - Include the effect of protection devices for both network and converter-interfaced generating equipment; however, boiler/steam turbine models are not required.
    - To mitigate any issues discovered, examine fast-acting reactive power response devices during and following disturbances (FACTS, synchronous compensators, and/or requiring wind/conventional generators' response).
- *Voltage stability:* When studying voltage stability, possibility of deploying reactive power control capabilities of wind turbines is an important assumption as this may result in unaffected or enhanced voltage stability.
- *Small-signal stability studies:* Modelling automatic voltage regulator (AVR) is required, including power system stabilizer settings for synchronous generation.
- *Frequency stability studies:*
    - Reduced inertia at times of high non-synchronous penetration will alter system response for both faults and contingencies. This is important to be studied, especially for small power systems.
    - Modelling inertia as well as droop and governor control settings of all units (both individual unit responses and system response to faults or contingencies) is important. Considering the fraction of generation participating in governor control and manoeuvrable capacity is important.
    - Consider that wind turbines can provide synthetic inertial response, depending on their operating point. Fast-acting load response or storage may also be included.
    - A reduced network representation may be sufficient.

References

3E, dena, EWEA, ForWind, IEO, NTUA, Senergy, SINTEF. (2011). Offshore Electricity Grid Infrastructure in Europe. http://www.offshoregrid.eu/images/FinalReport/offshoregrid_main-report_nov11.pdf

Boemer, J.C.; van der Meer, A.; Rawn, B.G.; Hendriks, R.L.; Ciupuliga, A.R.; Gibescu, M.; Kling, W.L.; Ferreira, J.A. (2011a). "Fault Ride-through Requirements for Onshore Wind Power Plants in Europe: The Needs of the Power System." *2011 IEEE Power and Energy Society General Meeting*, 24–29 July, Detroit, Mich., United States.

Boemer, J.C.; van der Meer, A.; Rawn, B.G.; Hendriks, R.L.; Gibescu, M.; van der Meijden, M.; Kling, W.L.; Ferreira, J.A. (2011b). "Network Fault Response of Wind Power Plants in Distribution Systems During Reverse Power Flows." *10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Farms*, 25–26 October, Århus, Denmark.

CIGRE (Conseil International des Grands Réseaux Électriques). (2001). "Modelling New Forms of Generation and Storage." Technical Brochure TF 38 01.10. Ref. No. 185.

CIGRE (Conseil International des Grands Réseaux Électriques). (2007). "Application and Required Developments of Dynamic Models to Support Practical Planning." Technical Brochure 312, CIGRE Working Group C1-04. Available on www.e-cigre.org.

Ciupuliga, A.R.; Gibescu, M.; Pelgrum, E.; Jacobs, P.G.H.; Jansen, C.P.J.; Kling, W.L. (2012). "Round-the-Year Security Analysis with Large-Scale Wind Power Integration." *IEEE Transactions on Sustainable Energy* (3:1); pp. 85–93.

Deutsche Energie-Agentur (dena). (2010). "dena Grid Study II—Integration of Renewable Energy Sources in the German Power Supply System from 2015–2020 with an Outlook to 2025. Summary of the Main Results by the Project Steering Group." Available at http://www.dena.de/fileadmin/user_upload/Publikationen/Erneuerbare/Dokumente/Summary_dena_Grid_Study_II.pdf .

EirGrid and SONI, 2010. All island TSO facilitation of renewables studies, June 2010. Available: http://www.eirgrid.com/renewables/facilitationofrenewables/.

ENTSO-E (European Network of Transmission System Operators for Electricity). (2011). "Offshore Transmission Technology." Available at https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/SDC/European_offshore_grid_-_Offshore_Technology_-_FINALversion.pdf.

ENTSO-E (European Network of Transmission System Operators for Electricity). (2012). *Ten-Year Network Development Plan 2012* (TYNDP 2012 Package). Includes six Regional Investment Plans, one Ten-Year-Network-Development Plan, and one Scenario Outlook and Adequacy Forecast. Available at https://www.entsoe.eu/system-development/tyndp/tyndp-2012/.

Eto; J. H. Undrill; J. Mackin ;P. Daschmans; R. Williams; B. Haney; B. Hunt; R. Ellis; J. Illian; H. C. Martinez; M. O'Malley; K. Coughlin. (2010). Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation. Lawrence Berkley National Laboratory, LBNL-4142E, Dec 2010.

Gautam, D; Vital, V; Harbour, T. (2009). “Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems.” *IEEE Transactions on Power Systems*. Vol. 24, No. 3, pp. 1426–1434. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=4912364&contentType=Journals+%26+Magazines&searchField%3DSearch_All%26queryText%3Dgautam+vittal

Brisebois, J.; Aubut, N. (2011). “Wind farm inertia emulation to fulfill Hydro-Québec's specific needs.” *Power and Energy Society General Meeting, 2011 IEEE.* DOI: 10.1109/PES.2011.6039121 http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=6039121&contentType=Conference+Publications&searchField%3DSearch_All%26queryText%3Dbrisebois

Knüppel, T.; Akhmatov, V.; Nielsen, J.N.; Jensen, K.H.; Dixon, A.; Østergaard, J. (2009). “On Small-Signal Stability of Wind Power System with Full-Load Converter Interfaced Wind Turbines.” *American Wind Energy Association WINDPOWER Conference & Exhibition*, 4–7 May, Chicago, Ill.

Matevosyan, J. (2006). Wind power integration in power system with transmission bottlenecks. PhD study, KTH, Sweden. Available at: http://www.diva-portal.org/kth/theses/abstract.xsql?dbid=4108.

Miao, Z.L.; Fan, L.; Osborn, D.L.; Yurarajan, S. (2009). “Control of DFIG-Based Wind Generation to Improve Interarea Oscillation Damping.” IEEE Transactions on Energy Conversion, Vol. 24, No. 2, pp, 415–422. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=4957574&contentType=Journals+%26+Magazines&ranges%3D2009_2009_p_Publication_Year%26searchField%3DSearch_All%26queryText%3Dmiao+wind

Miller, N.; Shao, M.; Venkataraman, S. (2011). *CAISO Frequency Response Study*. Schenectady, NY, United States: GE Energy.

Rawn, B.G.; Gibescu, M.; Kling, W.L. (2010). “Kinetic Energy from Distributed Wind Farms: Technical Potential and Implications.” In Proceedings, *Innovative Smart Grid Technologies Europe*, 22–13 October, Gothenburg, Sweden.

Rudion, K.; Orths, A.; Abildgaard, H.; Eriksen, P.B.; Søgaard, K. (2011). “Energy Market - Driven Offshore Power System Operation.” In *Proceedings of 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 25–26 October, Århus, Denmark.

Ruttledge, L.; Flynn, D. (2011). “System-wide inertial response from fixed speed and variable speed wind turbines.” In *2011 IEEE Power and Energy Society General Meeting*, 24–29 July, Detroit, Mich., United States.

Ruttledge, L.; Miller, N.; O’Sullivan, J.; Flynn, D. (2012). “Frequency Response of Power Systems with Variable Speed Wind Turbines.” *IEEE Transactions on Sustainable Energy* (3:4); pp. 683–691.

Smith, J.C.; Osborn, D.; Zavadil, R.; Lasher, W.; Gómez-Lázaro, E.; Estanqueiro, A.; Trötscher, T.; Tande, J.O.; Korpås, M.; van Hulle, F.; Holttinen, H.; Orths, A.; Burke, D.; O’Malley, M.; Dobschinski, J.; Rawn, B.; Gibescu, M.; Dale, L. (2012). Transmission planning for wind energy in the United States and Europe: status and prospects. WIREs Energy Environ 2013, 2, pp. 1–13. doi: 10.1002/wene.8.

Tande, J. O. and Uhlen, K. (2004). Cost analysis case study of grid integration of larger wind farms. Wind Engineering, Vol. 28, No. 3, pp. 265–273.

van der Meer, A.A.; Hendriks, R.L.; Kling, W.L. (2009). "A Survey of Fast Power Reduction Methods for VSC Connected Wind Power Plants Consisting of Different Turbine Types." *2nd EPE Wind Energy Chapter Seminar*, KTH, 23–24 April, Stockholm, Sweden.

van der Meer, A.A.; Hendriks, R.L.; Kling, W.L. (2010). "Combined Stability and Electro-Magnetic Transients Simulation of Offshore Wind Power Connected Through Multi-Terminal VSC-HVDC." In *2010 IEEE Power and Energy Society General Meeting*, 25–29 July, Minneapolis, Minn. United States.

Vittal, E.; O'Malley, M.; Keane, A. (2010). "A Steady-State Voltage Stability Analysis of Power Systems with High Penetrations of Wind." *IEEE Transactions on Power Systems* 25(1); pp. 433–442.

7 Analysing and Presenting the Results

Hannele Holttinen, Lennart Söder, Michael Milligan, Juha Kiviluoma, Mark O'Malley

When there is a change in a power system of any kind, then this will have an impact on several other components. This relates to new loads, new transmission lines in a system, new interconnections to other systems, new power plants of any kind etc. If, e.g., a new transmission line is built to a neighbouring system then this will have an impact on reserves, voltage levels, economy of other power plants etc. Integration studies in reality should be (and are often) performed for any changes in the system to see the whole perspective. Here we mainly discuss the specific case of wind power integration, but the same methods could be used also to study other changes in the system. If wind power is compared with other investments, then an integration study should also be performed for the other alternative.

When analysing simulation results, it is possible to iterate back to earlier stages in the flowchart (Figure 1), including initial assumptions. If the impact of wind power proves difficult or costly to manage, more flexibility in operational practice is needed. This underlines the importance of the main setup and the portfolio chosen as the basis for the results, as wind integration study purpose and the main setup chosen will have crucial impacts on the results.

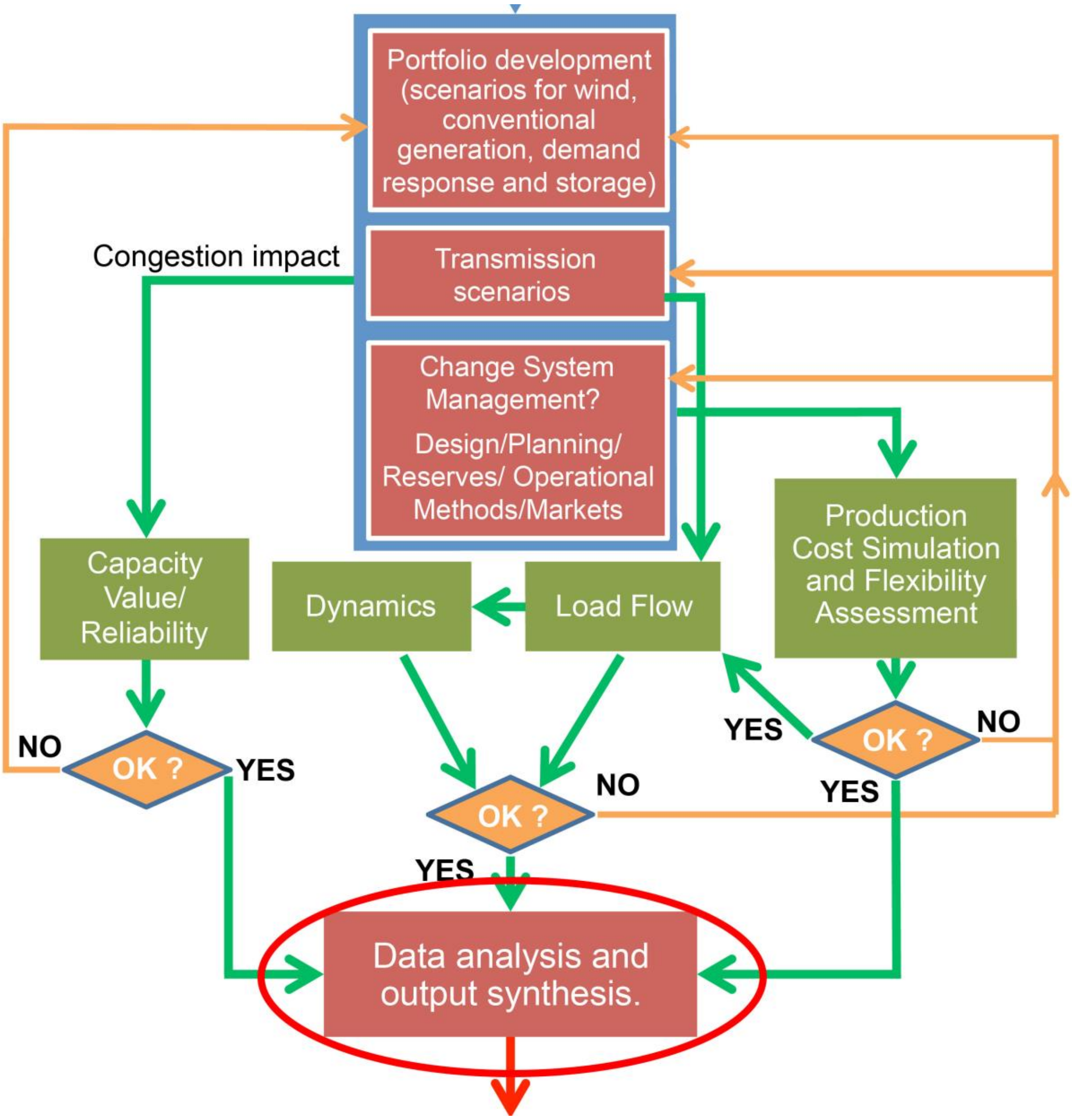


Figure 16. Wind integration study components: data analysis and output synthesis.

Main assumptions regarding access to enablers like flexible transmission to neighbouring areas, flexible generation, or demand assets will influence the results. Both technical flexibility and operational flexibility can change for future systems. At higher penetration levels, the methods and tools used for planning and operation, like allocation of reserves, need to be adapted. Successful wind integration means changing the operation of the power system from how systems have been traditionally operated.

A comparison of results for different methods is challenging. It is important to present results using metrics that other studies have used, and to state the wind penetration level and the size of the power system, as well as all relevant assumptions and limitations of the methodology chosen (Holttinen et al. 2009; Holttinen et al. 2013). Results of integration studies should be discussed in detail to keep in mind the assumptions made and weaknesses of the estimates. It is challenging to draw out the system cost for a single form of generation because system services exist for all loads and generators. For example, in the case of transmission costs induced by wind power (except in the case of a radial connection), additional transmission typically provides a reliability benefit beyond the benefit of connecting the generator in question, and thus allocation of this cost to wind power only is not accurate.

This section starts with general discussion about the challenges of determining integration costs. The impact of wind power on transmission losses, grid bottleneck situations, and grid reinforcement needs are discussed in Section 7.2. Impacts on the balancing the power system, including cycling and operation of conventional power plants are discussed in Section 7.3. How to present the results with a list of limitations in the assumptions is discussed in Section 7.4.

7.1 Comparison of Costs and Benefits

Many studies aim to estimate integration costs. The concept of integration cost is widely agreed upon, but it is not possible to define it rigorously. In practice it is challenging, if not impossible to separate system costs to different generators in an accurate way. The concept of integration cost has been applied in several ways, often referring to the cost to the system of accommodating the variability and uncertainty of wind power. Transmission grid expansion or reinforcement may also be needed, and those costs are considered as part of overall cost of connecting wind power to the grid. In some studies, grid reinforcement costs are considered as part of integration costs. A primary component of wind integration cost consists of the increase in the use of operating reserves and the balancing market used to maintain the system balance; however, balancing can be supplied from existing generation that is moved to lower output levels as the wind power increases. Integration costs do not include the costs for installing new power plants (capital costs) and connecting them to the existing grid.

From the basic definition of integration cost, the following is concluded:

- Integration cost should in principle be possible to be calculated for any power system investment (e.g., power plant of grid expansion). Examples of how integration costs may be incurred by other types of power plants, such as new base load generation and new higher contingency levels, are presented in Milligan (2011).
- Integration cost depends on the assumptions regarding the generation mix in the replaced and remaining system and operating costs. During periods of increasing levels of installed wind power, the composition of both existing plants and additions will significantly influence the ability of the power system to integrate wind power in a cost-effective way. Likewise, the transmission configuration and any potential extensions, along with operating procedures, can significantly influence the results.

The need for transmission capacity and balancing resources of power systems will increase with high amounts of wind power. However, correctly extracting costs related to them is very difficult and should be undertaken with great care because these costs are not observable (Milligan et al. 2012). The approach usually taken in wind integration studies is to quantify the incremental increases in costs for power systems after accounting for the energy cost. Although it is difficult to extract the cost of variability and uncertainty from wind integration, it is relatively straightforward to assess the total operational cost for both no-wind and wind cases, and these operational costs can be compared. Here the challenges lie in how to choose the non-wind case to be able to extract the wind-induced costs only.

Integration costs of wind power should be compared to something, like the production costs or market value of wind power, or integration cost of other production forms. A fair comparison between power systems with differing amounts of wind power should in principle have systems with the same reliability but also common levels of carbon dioxide emissions or at least take the CO2 emission costs into account. The value of the capacity credit of wind power can also be stated and considered when the amount of required total installed capacity is to be calculated.

When different alternatives for the future power system expansion are to be considered, then the total performance from economic, reliability, security, and environmental point of view are to be considered and then the same requirements from all these aspects are to be compared. Cost-benefit analyses can be carried out that examine the all-in cost and benefits of wind power compared to other generation and transmission options, including capital and operating cost. These cost benefit comparisons are preferable over wind integration cost estimates, which cannot be rigorously defined.

7.2 Impacts on Transmission Grids: Losses, Bottleneck Situations, and Reinforcement Needs

The impact of wind power on transmission losses and grid bottleneck situations can be significant in some cases and therefore may need to be assessed. The changes in use of the power lines as a result of increasing wind power production can bring about power losses or benefits and changes in bottleneck situations. Depending on its location, wind power may at its best reduce bottlenecks, but at another location result in more frequent bottlenecks.

The commonly used method of detailed calculation for a limited amount of snapshot load and generation situations can give indications on whether the siting of wind turbines relative to load and other generation will increase or decrease the transmission losses and bottleneck situations. A full estimation involves assessing how often certain load levels occur and simulating a large part of the cases. An example of a round-the-year approach can be seen in Ciupuliga et al. (2012), where many combinations of load and generation can be studied by looking at one or more wind years with hourly resolution.

Results from load flow simulations (see Section 6.1) will reveal the need for transmission reinforcements. If transmission adequacy needs associated with wind power integration are of concern for only a small fraction of the year, network investments can potentially be postponed using, for example, curtailment, redispatch, or dynamic line ratings to increase transmission line capacity and co-ordinated control using FACTS devices or VSC-HVDC. For this analyses also, more simulations than just a few snapshots are needed.

Transmission cost is the extra cost in the transmission system when wind power is integrated. Either all extra costs are allocated to wind power, or only part of the extra costs are allocated to wind power—grid reinforcements and new transmission lines often benefit also other consumers or producers and can be used for many purposes, such as increased reliability and/or increased trading. One difficulty with assigning transmission cost to any specific generator (except in the case of a radial connection) is that additional transmission typically provides a reliability benefit beyond the benefit of connecting the generator in question.

In assessing the costs of grid reinforcement needs due to wind power (e.g., on a $/MW or $/kWh wind basis), one should be aware that due to the large amount of location and time-specific conditions, they cannot be directly compared from plant to plant or from country to country. Costs will depend on where the wind power plants are located relative to load and grid infrastructure. In addition, costs are dependent on the “grid situation” at the time instant the generator is connected. The same wind power plant, connected at a different time instant, therefore may lead to different grid reinforcement costs. Moreover, the grid reinforcement costs ($/MW) are not continuous; there can be single, very high cost reinforcements. Cost-benefit analyses of transmission measures should also take account of the positive or negative impact of wind power on transmission losses and grid bottleneck situations.

7.3 Wind Power Impacts on Thermal Units and Balancing

Balancing related impacts are impacts on reserve requirements (see Section 3.3 Reserve Allocation) as well as several operational impacts that can be extracted from production cost simulations (UC and economic dispatch, see Section 5.1 Production Cost Simulation):

- Positive impact of lower operating costs for the system due to avoided fuel used, and decrease in emissions
- Decrease of operating time of conventional units
- Increased cost for thermal power plants as $/MWh due to decreased efficiency
- Cycling costs (including start-up costs as well as ramping costs with wear-and-tear costs and reduced reliability),
- Ramping capability (see Section 5.2 Flexibility Assessment)

Increasing levels of wind penetration of wind in power systems can have significant impacts on other types of generating plants, including nuclear, coal, gas, oil, and hydro units. The impacts can be separated into two categories: markets and physical impacts. Market impacts occur due to the almost zero incremental cost of wind and/or "priority" dispatch effects that displace other generation in the merit order and subsequently depress the energy price. This "merit order effect" is well documented in the literature and is causing a significant debate in the industry, because one of its consequences is reduced revenue through energy markets and hence reduced revenue for all generation including wind itself (Munksgaard and Morthorst 2008; Goransson and Jonsson 2011). This impact is coupled with the physical impact of reduced running hours for other generation, compounding the revenue loss, as well as more starts and ramping (Troy et al. 2010). Moderate to high wind energy penetration levels can induce cycling impacts on the conventional generation fleet. These impacts include starts and stops, and more frequent and steeper ramping. This may result in increased wear-and-tear and the need for more maintenance, as well as running in in less than optimal conditions: the result is a potential increase in cycling costs. The cycling costs are very difficult to estimate and it is the subject of much debate and analysis (Lefton 2004). The overall system cost impacts have been estimated, and mitigation strategies are being proposed (Troy et al. 2012; Lew et al. 2012a and 2012b). Integration studies should take this into account if data can be made available.

It is not straightforward to set the assumptions in the portfolio development phase (see Section 3.1 Generation Portfolio and Transmission Scenarios) in a way that the output of the production cost simulations will be able to capture costs related to wind power integration. Basically there will be two simulation runs, to be able to subtract the costs and get a proxy for wind integration cost. Even if the total costs for power systems may increase due to wind power (that in most cases is still more expensive than conventional power plants), the operating costs of power systems will be reduced due to the use of wind power. This is because the bulk of operating costs come from fuel costs and wind power will replace fossil fuel use. At the same time costs due to emissions are also reduced. The integration cost is then actually the difference of full credit for operating cost reduction compared with cost for system operation with increasing variability introduced by wind power. One attempt of capturing cost of variability is by comparing simulations with flat wind energy to varying wind energy (Enernex 2006; Meibom and Weber 2009). However, there are some caveats in this method as the two simulated cases will also result in other cost differences than just the variability cost (Milligan and Kirby 2009). Also production cost calculations may not always indicate the proper power system beneficiary, depending on the presence of underlying bilateral contracts, about which information may be difficult to obtain.

Another approach is to attempt to capture total costs and benefits of different portfolio rather than wind power integration costs (an example can be seen in AIGS 2008). Different portfolios of generation mix, with different amounts of wind power, should be constructed with a generation planning model plus a reality check.

When estimating increases in operating costs, it is important to note whether a market cost has been estimated or the results refer to technical costs for the power system. Technical cost is the increase in the costs that the power plants actually see, whereas a market cost can include a profit to the producers that provide extra flexibility. This means that a market cost includes transfer of money from one actor to another actor, while technical cost implies a cost for the whole system. Most studies so far have concentrated on the technical costs of integrating wind into the power system. Also cost-benefit analysis work is emerging. The benefit when adding wind power to power systems is reducing the total operating costs and emissions as wind replaces fossil fuels.

Regarding wind power impacts on reserves:

- Some studies have a goal of estimating the increase in operational cost from obtaining this additional reserve. This can usually be calculated by taking the difference in production cost from two production simulation runs, one that includes the extra reserve, and the other that does not include this reserve.
- An increased level of reserves caused by wind power may be supplied by conventional generators that are used to supply energy in the non-wind case, and are used to supply less energy and more reserve in the wind case. This is a critical distinction, and failure to understand this basic principle can lead to erroneous statements. During times when wind power output increases, other generating units must back down, allowing them to provide up-reserve if needed.
- A wind integration study can examine some of the alternative approaches for providing operating reserves. Reserves usually come from existing flexible generation. In addition, it is possible that part of the increased reserve can come from non-spinning resources or market products, also including demand side and storage options. These possibilities should be examined, along with potential changes in the institutional framework, such as changes in market time-steps, size, or product availability.

Regarding balancing on a longer time scale, reflecting the adequacy of power systems during peak load demands, the capacity value of wind power is relevant to calculate. The capacity value of wind power will be lower than for conventional power plants. It is usually close to average power produced during times of peak load situations, and will decrease with higher wind penetration levels (Holttinen et al. 2009).

Some recent work has introduced a new component of integration cost: the capacity cost of wind power. This is a controversial concept, and is not widely accepted. Wind power has a relatively low capacity value (which may range from 5–40% of rated capacity) compared to many other types of generation (which can range up to 90% or more of rated capacity). Proponents of this concept argue that there is a system cost when wind power is added because addition generation must also be added to the system to compensate for wind power’s low capacity value. For example, if a wind plant has a 20% capacity value and a benchmark unit is 90%, then the 70% gap must be supplied by a capacity resource such as a combustion turbine that can achieve the 70% gap in capacity value. However, this analysis should compare the two options with energy-equivalent generation sources. Another important thing is the cost used for of this back-up capacity that is only used for critical peak load hours unless the wind does not blow. Söder and Amelin (2008) argue that open cycle gas turbines or similar peaking capacity provides the most appropriate benchmark if this approach is taken.

Opponents of this view argue that, historically, generation has rarely, if ever, been liable for providing characteristics that it does not possess. For example, most power plants that have been designed for base load operation are unable or unwilling to ramp and cycle, both of which are needed to reliably operate the power system. Some units are unable to provide AGC, which is another needed service. Yet these units are not liable for providing AGC to the system. Ancillary services are needed by the system, and must be provided but not by units that are unable to perform the service. Further, wind power may be added to the system as an energy resource, and not a capacity resource. Thus, there may be no need for additional capacity to bring the effective contribution of wind power plus a companion generator up to a 90% capacity value.

7.4 How to Present the Results

In order to evaluate the result from a certain study, it is important to consider the setup of the study as well as the simulation method. If results are to be compared from different studies, it is essential to understand the methods and data that provided the results. Comparing results from the integration study to previous work is easier if some basic things about the study are reported.

It is recommended to report the following along with the results:

- *Penetration level of wind power studied:* The penetration of wind power can be expressed by various measures. Often either energy or capacity metrics are used: wind power production as a percentage of gross demand (energy) and wind power capacity as a percentage of peak load (capacity). However, these measures neglect the presence of interconnecting capacity with neighbouring countries, although the cross-border interconnections are often the key to efficient power system operation. In particular, for the case of high wind and minimum load, operational constraints may be alleviated through utilising cross-border transmission capacity for export of (excess) generation. It is thus relevant to express wind penetration level in terms of wind capacity in percentage of the sum of minimum load and cross-border capacity.
- *Power system size and general characteristics:* Power system size is peak load and general characteristics include thermal/hydro dominated and the amount of flexible/inflexible units.
- *How wind power is added:* What are the differences in scenarios for wind and non-wind cases?
- *Basic assumptions regarding flexibility, interconnection, operational practices*
- *Method and simulation tool limitations*

Many wind integration studies give estimated impacts as an increase in reserve requirements (MW), increase in grid reinforcement needs (length for different kV lines), and integration costs ($/MWh, €/MWh). Many studies give the results in less comparable ways, like impacts on the scheduling of other power plants and exports, impacts on the stability of the transmission grid, and impacts on adequacy of power. Different metrics for the results have been used in the studies—results as monetary value per megawatt-hour of wind or per megawatt-hour of total consumption (reflecting the increase in consumer price). There are also results as a percent of more wind power production needed to cover extra losses.

Regarding reserve requirements, there is no simple way of presenting the result of dynamic, varying reserve requirement. One approach would be to present it as a duration curve or a range over an average reserve level, but for this at least 1 year of data should be available.

It would be good to mention curtailment of wind explicitly in final results. The net generation of wind power is relevant. Curtailed amount can be used for example regarding transmission investment decisions.

7.5 Study Limitations Arising from Assumptions

The results of a study will depend on assumptions and modelling framework, along with the input data. The ideal methodology for simulations would mean taking all possible market and grid dynamic aspects into account, and cover several years with a small time step (less than a second). This is impossible in practice, although the simulation tools are developing to this direction. Limitations arise from the simulation methodology and from assumptions that need to be made when simulating the system operation. An important challenge is uncertainty in the basic scenario concerning units, and loads and prices in a future system when higher amounts wind power will happen. It is important when conclusions are drawn to consider the consequences of the assumptions chosen. Because not all wind integration studies have the same objective, there may be differences in assumptions that are based upon the objective.

The setup for the study may give rise to limitations. For example, comparing one system with and one without wind power, where the remaining system is the same, the prices (set by marginal costs) will be lower in the system with wind power, since units with highest marginal costs will be replaced when it is windy. This is mainly a result of study setup and is generally valid for any kind of production investments in a certain system using this method.

There are other examples of limitations that arise if the iteration loops in the flow chart are not used (see Figure 1). Making a generation expansion plan before the wind integration study with no time to re-plan based on the integration study results and re-run the study may result in showing results that wind integration is not feasible. Another example is that large amounts of wind power will result in more volatile prices (high prices during high load/low wind, low prices during high wind/low load), which in reality will result in changed behaviour of consumption and investments in flexible power plants and/or transmission to neighbouring systems. Reliability constraints from transmission or capacity adequacy or reserve margins will require an iteration to change the installed capacity of the remaining power plants, the transmission grid, the operational methods or the reserves.

Examples for listing key assumptions:

- Whether wind power is added as an energy source only, or whether the wind power will support new load growth and/or displace existing or new generating capacity
- The level of detail regarding the simulation model, including the time step, reserve policies, general operating practice
- Source of the wind power data; source and method used to simulate wind power forecasts
    - Whether multiple forecast time scales are used
    - How the modelled forecast technology compares to current state-of-the-art
- Unit commitment time steps and whether UC is repeated as new information becomes available closer to real-time
- Assumptions regarding environmental restriction, including emission pricing
- Method for calculating flexibility reserve
- Level of detail in representing the transmission system
    - Nodal
    - Zonal
    - How are interconnections with neighbouring systems modelled

- Level of detail on modelling generation, including multiple modes for combined cycle plants, run-of-river vs. reservoirs in hydro systems, etc.
- Whether operating and market rules are based on current practice or potential future practices
- The level of investment in other generation and transmission
    - Generation mix
    - Flexibility characteristics of the generation mix
- Whether perfect competition is assumed in the electricity markets
- Whether wind plant controls are allowed to provide for ancillary services from wind plants and the impact that has on integration

Enablers for cost-efficient integration of wind power include flexible intra-day markets, use of continually updated wind power forecasts, flexible trading with neighbouring systems, efficient treatment of the limiting effect of handling large geographical spreading of total wind power, consideration of price sensitivity in the demand, consideration of expansion of the transmission network, and consideration of a cost-efficient use of system wide balancing resources. Important issues include how the larger footprint is taken into account (use of interconnections) and whether the balancing is performed in an isolated system versus within a larger system. This is also important from a reliability point-of-view because smaller synchronous systems do not usually use as high reliability targets.

The matrix developed in (Söder and Holttinen 2008) can be used as a check-list, to find out whether the approach has been conservative or whether some important aspects have been omitted, producing either high or low estimates for the impacts. The following summary of different issues to be considered comes from the Task 25 summary report (Holttinen et al. 2009).

Table 4. Summary of Issues

Set Up		
A	**Aim of Study**	1 what happens with x GWh (or y GW) wind 2 how much wind is possible 3 other:
M	**Method to Perform Study**	1 add wind energy 2 wind also replaces capacity 3 load is increased same amount of GWh as wind 4 optimal system design 5 other: For capacity credit also: (a) chronological, using wind power and load profiles (b) probabilistic
S	**Simulation Model of Operation**	1 deterministic simulation, one case 2 deterministic simulation several cases 3 deterministic planning with stochastic wind forecast errors 4 Stochastic simulation several cases 5 other:
Simulation Detail		
R	**Resolution of Time**	1 day/week 2 hour 3 minute/second DURATION of simulation period:

P	**Pricing Method**	1 costs of fuels etc. 2 prices for trading with neighbours, historical market prices 3 perfect market simulation (each actor maximises its benefit according to some definition considering the physical and legal constraints) 4 market dynamics included (different actors on the market make investments or change their behaviour depending on the market prices) 5 other:
D	**Design of Remaining System**	1 constant remaining system 2 optimised remaining production capacity 3 optimised remaining transmission 4 changed operation due to wind power 5 perfect trading rules 6 other:
Uncertainty and Balancing		
I	**Imbalance Calculation**	1 only wind cause imbalances 2 wind+load forecast errors cause imbalance 3 wind+load +production outages cause imbalances 4 other:
B	**Balancing Location**	1 dedicated source 2 from the same region 3 also outside region 4 other:
U	**Uncertainty Treatment**	1 transmission margins: 2 hydro inflow uncertainty: 3 wind forecasts: (a) assume no knowledge and large margins for wind 0…full capacity, (b) assume perfect forecast for wind, (c) persistence forecasts for wind, (d) best available forecasts, specify what level of forecast error assumed 5 load forecasts considered: 6 thermal power outages considered: 7 other: TIME HORIZON for forecasts assumed in the simulation (1–2 hours…day-ahead)
Power System Details		
G	**Grid Limit on Transmission**	1 no limits 2 constant MW limits 3 consider voltage 4 N-1 criteria 5 dynamic simulation 6 other MULTI-AREA SIMULATIONS: limits inside the whole area and limits outside the simulated area separately
H	**Hydro Power Modelling**	1 head height considered 2 hydrological coupling included (including reservoir capacity) 3 hydrological restrictions included (reservoir level, stream flows) 4 availability of water, capacity factor, dry/wet year 5 hydro optimisation considered 6 limited, deterministic run-of-river 7 interaction with hydro resources not significant 8 other:
T	**Thermal Power Modelling**	1 ramp rates considered 2 start/stop costs considered 3 efficiency variation considered 4 heat production considered 5 other:

W	**Wind Power Modelling**	1 time series: (a) measured wind speed + power curve (how many sites) (b) wind power from wind power plants (how many sites) (c) re-analysis wind speed + power curve (how many sites) (d) time series smoothing considered (how) 2 wind power profiles: (a) climatic, e.g. lowest / highest temperature, (b) hour of day, (c) season, e.g. only winter, (d) load percentile 3 synchronous wind data with load or not 4 installation scenarios for future wind power distribution (put together scenarios by association, government plans; according to projected regional capacity factors…); specify geographical distribution of wind 5 other:

The term *dynamics* here means both power system dynamics (milliseconds to minutes/hours) as well as investment dynamics (changed prices and price volatility ➔ changed investments).

7.6 Checklist: Analysing and Presenting Results

Checklist of Key Issues: Analysing and Presenting Results

- If the results show unexpectedly high and costly impacts of wind power to the system, consider the iteration loops. Changing operational practices may prove cost effective, or generation or transmission scenarios may be in adequate.
- When extracting results for the impacts, select the cases to compare with care and report the methodology and possible caveats in the findings. Assessing integration costs is especially challenging.
- Present the results stating penetration level of wind, size and type of power system and the main assumptions and limitations arising from these .

References

AIGS. (2008). All Island Grid Study. Available at: http://www.dcenr.gov.ie/Energy/North-South+Co-operation+in+the+Energy+Sector/All+Island+Electricity+Grid+Study.htm, 2008.

Ciupuliga, A.R.; Gibescu, M.; Pelgrum, E.; Jacobs, P.G.H.; Jansen, C.P.J.; Kling, W.L. (2012). "Round-the-Year Security Analysis with Large-Scale Wind Power Integration." *IEEE Transactions on Sustainable Energy* (3:1); pp. 85–93.

EnerNex/WindLogics. (2006). Minnesota Wind Integration Study Final Report. Vol I, prepared for Minnesota Public Utilities Commission, Nov. 2006. http://www.puc.state.mn.us/portal/groups/public/documents/pdf_files/000664.pdf

Göransson, L.; Johnsson, F. (2011). "Large Scale Integration of Wind Power: Moderating Thermal Power Plant Cycling." *Wind Energy* (14:1); pp. 91–105.

Holttinen, H.; Meibom, P.; Orths, A.; van Hulle, F.; Lange, B.; O'Malley, M.; Pierik, J.; Ummels, B.; Tande, J.; Estanqueiro, A.; Matos, M.; Gomez, E.; Söder, L.; Strbac, G.; Shakoor, A.; Ricardo, J.; Smith, J.C.; Milligan, M.; Ela, E. (2009). *Design and Operation of Power Systems with Large Amounts of Wind Power*. Final report, Phase one 2006–2008, IEA Wind Task 25, VTT Research Notes 2493. Available at http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2493.pdf.

Holttinen, H.; Kiviluoma, J.; Robitaille, A.; Cutululis, N.A.; Orths, A.; Hulle, F. van; Pineda, I.; Lange, B.; O'Malley, M.; Dillon, J.; Carlini, E.M.; Vergine, C.; Kondoh, J.; Gibescu, M.; Tande, J.O.; Estanqueiro, A.; Gomez, E.; Söder, L.; Smith, J. C.; Milligan, M.; Lew, D. (2012). Design and operation of power systems with large amounts of wind power. Final summary report, IEA Wind Task 25, Phase two 2009–2011. Espoo, VTT. 81 p. + app. 13 p. VTT Technology; 75 http://www.vtt.fi/inf/pdf /technology/2012/T75.pdf

Lefton, S. (2004).“Profitable Operation Requires Knowing How Much It Costs to Cycle Your Unit.” *Combined Cycle Journal* (2Q); pp. 49–52.

Lew, D.; G. Brinkman; N. Kumar; P. Besuner; D. Agan; S. Lefton. (2012). Impacts of Wind and Solar on Fossil-Fueled Generators. Presented at IEEE Power and Energy Society General Meeting San Diego, California July 22–26, 2012. Available at http://www.nrel.gov/docs/fy12osti/53504.pdf.

Lew, D.; G. Brinkman; E. Ibanez; B.-M. Hodge; J. King. (2012). The Western Wind and Solar Integration Study Phase 2. Proceedings of 11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants Conference. Lisbon, Portugal.

Meibom, P.; Weber, C.; Barth, R.; Brand, H. (2009). Operational costs induced by fluctuating wind power production in Germany and Scandinavia. IET Renewable Energy Generation, Volume 3, Issue 1, p. 75–83, March 2009.

Milligan, M.; Ela, E.; Hodge, B. M.; Kirby, B.; Lew, D.; Clark, C.; DeCesaro, J.; Lynn, K. (2011). Cost-Causation and Integration Cost Analysis for Variable Generation. 37 pp.; NREL Report No. TP-5500-51860

Milligan, M.; Hodge, B.; Kirby, B.; Clark, C. (2012). Integration Costs: Are They Unique to Wind and Solar Energy? Preprint. 12 pp.; NREL Report No. CP-5500-54905. http://www.nrel.gov/docs/fy11osti/51860.pdf

Milligan, M.; Kirby, B. (2009). “Calculating Wind Integration Costs: Separating Wind Energy Value from Integration Cost Impacts.” NREL Technical report TP-550-46275, July 2009. Available at http://www.nrel.gov/docs/fy09osti/46275.pdf.

Munksgaard, J.; Morthorst, P.E. (2008). “Wind Power in the Danish Liberalised Power Market—Policy Measures, Price Impact and Investor Incentives.” *Energy Policy* (36:10); pp. 3940–3947.

Söder, L.; Amelin M. (2008). A review of different methodologies used for calculation of wind power capacity credit Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE 20–24 July 2008, pp. 1–5.

Söder L.; Holttinen H. (2008). On methodology for modelling power system impact on power systems. *International Journal of Global Energy Issues*, Vol. 29, 1–2, pp. 181–198.

Troy, N.; Denny, E.; O’Malley, M.J. (2010). “Base-Load Cycling on a System with Significant Wind Penetration.” *IEEE Transactions on Power Systems* (25:2); pp. 1088–1097.

Troy, N.; Flynn, D.; Milligan, M.; O’Malley, M.J. (2012). “Unit Commitment with Dynamic Cycling Costs.” *IEEE Transactions on Power Systems* (27:4); pp. 2196–2205.

8 Conclusions and Future Work

Wind integration studies have been maturing continuously as the state-of-the-art advances, with each study generally building on previous ones. The recommendations are based on current knowledge, and also recommendations will evolve as new knowledge in the area is obtained. Integration studies can be performed for any kind of changes in a power system since all changes often have technical and economic impact on other parts of the system.

A comprehensive wind integration study has many inputs and is built on numerous assumptions, which should be clearly described in the study. These may include the following:

- *Objective of the study:* what is included, and what is excluded
- *Existing power system data:* includes generation portfolio, power plant data, load data, transmission network, operational practice, power market structure, and wind plant size and location
- *Wind power related data:* detailed wind production data that correctly characterises plant performance and geographical spread, time-synchronised with load data, as well as data on wind and load uncertainty (forecast errors). Location of wind power plants for grid simulations.
- *Other assumptions that play a key role in results*: such as future scenarios of conventional generation and network characteristics, links to heat demand (in cases with combined heat and power plants), demand response possibilities, as well as fuel prices, taxes, CO2 allowances and emission limits.

Key tasks that comprise the study include the following:

- Data collection and quality checking
- Portfolio development: determining scenarios to be studied and base case for comparisons
- Impact of wind power on short term reserves as statistical data analysis
- Running capacity (resource) adequacy analysis to assess capacity value of wind power
- Running production cost simulations to see how wind power impacts the scheduling and dispatch of conventional generation, and operational costs of the system
- Running transmission network simulations to see that the transmission network is adequate
- Running iterations based on initial results if there is need to change the generation or transmission portfolio or operational practices
- Analysing the data and presenting the results

Depending on the penetration levels studied, some components of the study can be omitted. How low penetration is defined will depend on power system characteristics: 5% is low in some systems, whereas 10% (from yearly electrical energy, the gross demand) can be appropriate in others. For example, depending on the load and wind resource, challenging high penetration level situations can occur already before 10% of yearly penetration level in some systems. To start with, at lower penetration levels, portfolio development can just include the power system as it is operated today, and the main simulation components are production cost simulation and load flow, to see the impact of wind power to the other power plants as well as needs to upgrade transmission network. Impacts to reserve requirements may also be addressed. For higher penetration levels it will be more relevant to assess capacity value and dynamic stability and make a more detailed flexibility assessment. Even if capacity value of wind power is usually not critical at low penetration levels, it has often been included in the studies. And in many studies so far transmission network is not studied but simplified approach is taken with only production cost simulations. A full study is a complicated process especially taking into account all possible iteration loops.

There are important iteration cycles from the simulation parts to portfolio setup and operational practices that ensure the reliability of the system and also enable more cost-effective integration. The main assumptions will have a crucial impact on the results. The recommendations regarding simulation parts include how to take wind power into account as well as how to model the system to capture wind impacts. Results of integration studies should be discussed in detail to keep in mind the assumptions made and weaknesses of the estimates.

Some studies compare one or more wind power scenarios with alternatives. The details of these comparisons and assumptions regarding each scenario should be made clear because there are challenges in choosing the non-wind case such that the differences are due to wind addition only.

Integration study methodologies continue to evolve and new experience of real wind integration will emerge. Recommendations for the main steps and methodologies will be updated as part of continuing international collaboration under IEA Wind Task 25. Recommendations on how to operate power systems in future have a link to policy and market development. Areas of future work that may influence the recommendations in future include the following:

- Development of flexibility metrics and tools that can be used to evaluate the flexibility needs of the power system, and ways to achieve that flexibility
- Development of simulations tools that take into account the uncertainty of wind power in different time scales, and enable combining network constraints with UC and dispatch constraints
- Ways to set up simulation cases to be able to extract impacts and system costs. Production cost calculations may not always indicate the proper power system beneficiary, depending on the presence of underlying bilateral contracts, about which information may be difficult to obtain.
- Knowledge about stability issues with very high penetration cases. Future grids with more DC transmission.
- Implications of market design and/or regulatory processes for wind integration—it is not now well-known how markets should be designed to incentivise flexibility and generation resource adequacy in systems with high wind energy penetrations; regulatory processes for investment cost recovery are critical to success. There is also a need for studies on how large amounts of wind power impact different market elements so that market integration strategies or alternative market designs can be recommended. Where regulators are considering revisions to the market design or requirements for renewable portfolios, the impacts to cost recovery on authorized investments must be taken into account.