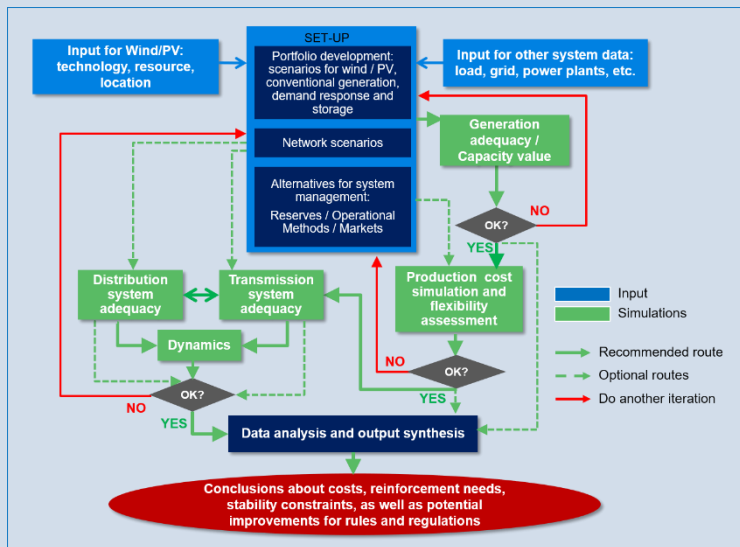# Recommended Practises for Wind and PV Integration Studies

IEA-Wind and IEA-PVPS Expert Group Report 16.2

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

EXPERT GROUP REPORT ON
RECOMMENDED PRACTICES
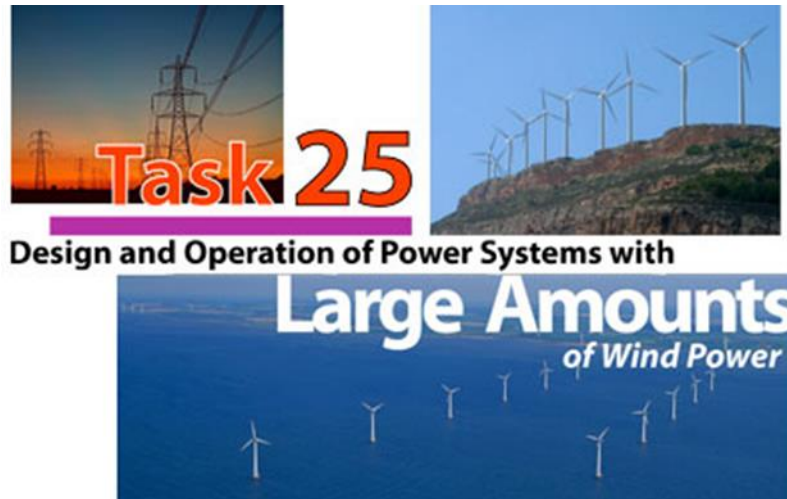**16. WIND/PV INTEGRATION STUDIES**

2nd EDITION, 2018

Submitted to the Executive Committees
of the International Energy Agency TCPs
for
Co-operation in the Research, Development, and Deployment
of Wind Energy Systems (IEA WIND)
and for
Photovoltaic Power Systems (IEA PVPS)

EXPERT GROUP REPORT ON
RECOMMENDED PRACTICES

16. WIND/PV INTEGRATION STUDIES

2nd EDITION, 2018

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Foreword

The International Energy Agency Technology Collaboration Programmes for Co-operation in the Research, Development and Deployment of Wind Energy Systems (IEA Wind) and Photovoltaic Power Systems Programme (IEA PVPS) are vehicles for member countries to exchange information on the planning and execution of national, large-scale wind and solar energy 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 TCP Tasks, Recommended Practices, Best Practices, or Expert Group Reports may be issued. These documents have been developed and reviewed by experts in the specialized 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 useful guidelines for 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.

This second edition of Recommended Practices 16 is a collaboration with IEA PVPS and IEA Wind TCP Tasks on grid integration. This edition updates recommendations for wind integration studies to also include solar PV. Additionally, this edition includes covers distribution as well as transmission network issues. The full report has been updated also to reflect recent findings in data and methods in use.

Preface

This Expert Group Report provides recommendations on how to perform studies of wind and solar PV integration. It is based on more than 10 years of work within the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) Task 25: Design and Operation of Power Systems with Large Amounts of Wind Power and the IEA Photovoltaic Power System Programme (PVPS) TCP Task 14: High Penetration of PV Systems in Electricity Grids.

The report is issued as an IEA Wind TCP Recommended Practices (RP) document to provide research institutes, consultants, and system operators with the best available information on how to perform an integration study. An integration study seeks to find issues to energy systems, as well as mitigation measures, to absorb certain amounts of generation from wind or solar energy. This is the first update of the recommendations, adding solar photovoltaics (PV) to the previous edition on Recommended Practices for Wind Integration Studies. The update also benefits from comprehensive review of recent integration studies based on real integration experiences and improved integration study methodologies for both wind and photovoltaics.

This Expert Group Report describes the methodologies, study assumptions, and inputs needed to conduct a wind and PV integration study. Findings and results from previous wind integration studies are discussed in the summary reports (Holttinen et al. 2009; Holttinen et al 2013; Holttinen et al 2016) and solar integration studies in (PVPS, 2014 and PVPS, 2017).

In RP 16, the Task 25 Expert Group developed a flow chart that outlines the phases of a complete wind integration study. In this second edition, the flow chart has been updated through close collaboration between Task 25 and Task 14 experts and is also applied to integration studies for photovoltaics (see Figure 2). The flow chart describes a comprehensive yet flexible process which can be adapted to the specific objectives and requirements of the individual study. It covers aspects ranging from transmission system integration down to the distribution level, which is of particular relevance for solar PV.

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.

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October 2018

Executive Summary and Summary of Recommendations

Challenge

Many individual wind and solar integration studies have been conducted in the past. The integration studies have evolved towards looking at the integration of wind and solar at the same time. Integration studies typically simulate a future power system with wind and solar contributions (share or penetration) varying from 5% to more than 50% of annual electrical supply. The studies seek to evaluate the potential impacts of wind and solar on the grid and on the operation of power generation. The power systems being studied and the data available about them vary significantly. Also, the goals and approaches differ, and thus the results are difficult to compare. The methodologies used in the studies are diverse and are still evolving.

The lack of reliable and comparable knowledge about the effects of variable renewable generation (i.e., wind and solar PV), including operational practices, can limit the large-scale development of renewable energy due to uncertainties about its impact. With the growth of wind and solar deployment and their tremendous potential, it is crucial that commonly accepted methodologies are applied to accurately assess integration issues. The first Recommended Practices/Best Practices to guide the conduct of wind integration studies was released in 2013. This report presents the current view of recommended methodologies, including solar photovoltaics (PV). As the field is still evolving, future development needs are also pointed out.

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/solar PV integration study. The findings are based on more than 10 years of international collaboration under IEA Wind TCP Task 25 and IEA PVPS TCP Task 14, 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 an integration study are organized according to the elements of this flow chart. Figure i shows the main setup of the study, input data needed, links between simulations and iterations to change main assumptions and finally analyzing the results. Even if the operation of a power system will be mimicked in many of the simulations, the integration studies are for future power systems and thus planning phase, and are not operational, real-time tools for system operators.

This Expert Group Report provides detailed recommendations for preparing wind/PV integration studies on power system operation (scheduling and dispatch with operating reserves) and power system generation capacity adequacy. Regarding power flow and dynamic/transient studies, this report presents the main points to consider when wind and solar PV is included in simulation analyzes, instead of detailed recommendations on methodologies.

This is because power flow and dynamic/transient studies are well established in engineering science with numerous text books giving adequate advice.[1]
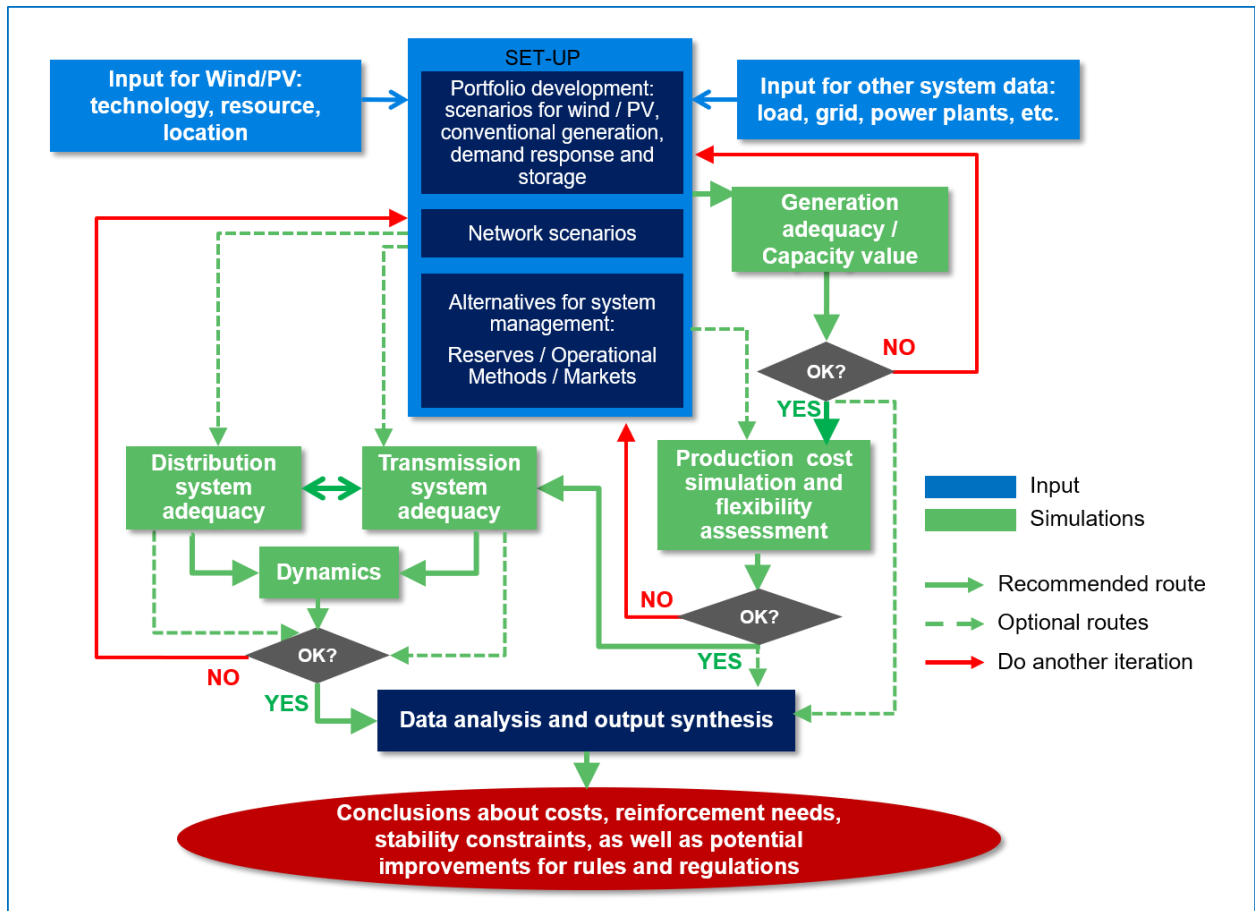

Figure i. Contents of a wind/PV integration study

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. Integration studies can also be made in phases. In this case, the first phase usually looks at the short-term impacts for lower shares of wind/PV for the current power system—mainly impacts on other power plants in production cost simulations or local distribution networks. More elaborate studies look at transmission network adequacy and congestion, as well as generation capacity adequacy for higher shares of wind/PV in future systems (including the capacity value of wind/PV).

The set-up phase can be iterative, taking results from generation/network adequacy simulations when forming scenarios. Iteration between network simulations and production cost simulations may also be needed. Network dynamics need to be assessed for larger shares of wind and solar.

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[1] See for example new CIGRE Technical Brochure under review by C4 "JWG C4-C6.35/CIRED Modelling of Inverter-Based Generation for Power System Dynamic Studies"

A comprehensive wind/PV integration study should clearly describe the 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, and general operational practice (including power market structure).
- *Wind/solar power related data:* detailed wind/solar production data that correctly characterizes plant performance and geographical spread, time-synchronized with load data, as well as data on wind, solar and load uncertainty (forecast errors). Location of wind and PV power plants for grid simulations, amount of wind/PV capacity added, and the share of wind and solar energy in electricity demand.
- *Other assumptions that play a key role in results*: 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:

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

Assessing significant wind/PV shares 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/PV. The results can show how changes to operating procedures, network code requirements and market structures could help ensure reliable and economic systems assuming high shares of variable power.

The Expert Group recommends the following procedures and considerations for conducting integration studies.

<u>Input data</u>

Rows in the following table describe the relevant components of the power system needed as inputs to different parts of an integration study.

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

	Capacity Value/ Power (resource) Adequacy	Unit Commitment and Economic Dispatch (UCED)	Power Flow	Dynamics
Wind/PV	Hourly generation time series for dispersed wind/PV energy covering the area. Especially for wind, more than 10 years recommended	5-minute to hourly generation time series of at least 1 year for dispersed wind/PV power covering the area	Wind/PV capacity at nodes, high and low generation and load snapshots, active and reactive power capabilities	Wind/PV capacity at nodes, high and low generation and load snapshots, dynamic models, operational strategies
Wind/PV Short-term Forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	May be needed in future	Not needed
Load	Hourly time series coincident with wind/PV data, at least 10 years recommended	5-minute to hourly time series coincident with wind/PV, of at least 1 year	Load at nodes, snapshots relevant for wind/PV 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	May be needed in future	Not needed
Network	Interconnection capacity, if relevant	Transmission line capacity between neighboring areas and/or circuit passive parameters	Network configuration, circuit passive and active parameters	Network configuration, circuit parameters, control structures
Other Power Plants	Rated capacities and forced outage rates	Min, max on-line capacity, start-up time/cost, ramp rates, min up/down times. efficiency curve, fuel prices	Active and reactive power capabilities, system dispatch	Dynamic models of power plants

Portfolio Development

<u>Generation and network (transmission and distribution) scenarios</u>

- When studying small amounts of wind/solar power, or short-term studies, integration can be studied by adding wind/solar to an existing, or foreseen system without major inaccuracies.
- For larger wind/solar shares[2] and long-term studies, the changes to the remaining system—mainly expedient generation portfolio and network infrastructure development—become increasingly beneficial and necessary, taking into account

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[2] What is considered a small or large share of wind/PV will depend on the power system studied, how large the area is where wind/PV is added, and how distributed it is built. Solar PV will tend to impact the system at lower shares than a well distributed wind power fleet. In most systems, 5-10% share of yearly electricity demand is considered a small share.

potential sources of flexibility (demand response) and technical capabilities of power plants (dynamic stability responses).

Operational methods

- Existing operational practices can be used as a starting point when studying small amounts of wind and solar power or short-term studies.
- For higher wind and solar shares, additional scenarios or operating practices should be studied. Assess market structures/design to enable operational flexibility.

Reserve requirements/allocation method

- Input data: Co-incident wind/PV and load time series (at least hourly) and wind/PV/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/PV 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/PV and load (and generation), keeping the same risk level before and after adding wind/PV. 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 shares, use dynamic, not static allocation methods for committing reserves.

Capacity Value of Wind and Solar Power

Data

- Gather chronological, time-synchronized wind/PV and load data that captures the correlation between wind/PV and load data. This is of paramount importance, and the robustness of the calculations is highly dependent on the volume of data collected–10 to 30 years is recommended. Data on generation unit installed capacity and forced outage rates is also required.

Methodology

- The preferred calculation method is a full effective load carrying capability (ELCC) method using chronological data on net load. 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/solar generation—wind/solar is

added as negative load, and load is increased until the same LOLE is reached as the one without wind/solar power

- If there is insufficient data for ELCC then approximation methods can give useful insights; however, the limitations of such should be recognized. The same methods can be applied for wind and solar separately, or in aggregate.

Production Cost Simulations and Flexibility Assessment

Data

- Time-synchronized (co-incident) input data for wind, PV and load with at least hourly resolution and one year is required. 10-15 min time steps and multiple years would be preferable. Capturing the spatial smoothing of wind/PV power production time series for the geographic diversity assumed is important. Wind/PV forecasting best practices should be used for the uncertainty of wind/PV power production, assumed for the year of study, with possibilities to update forecasts closer to delivery hour using rolling planning.
- Data for conventional power plants should include any possibilities or limitations of flexibility, like ramp rates and start-up times and costs. For hydro dominated systems the hydrological changes (wet/dry year) need to be captured and co-incident data is needed for run of the river hydro.

Methodology

- Capture system characteristics and response through operational simulations (Unit commitment and economic dispatch, or UCED).
- Model the flexibility options, as well as any constraints of flexibility. This includes generation unit ramping, minimum up/down times, minimum stable levels, start-up and shutdown limitations. Cycling impacts and the associated costs may also be important, as well as hydrological constraints in case of hydropower. The operational practices that may enable or limit flexibility to be used should also be taken into account.
- Take into account the possibilities of flexibility that exist in neighboring regions. To accurately model the limitations of interconnections, the neighboring system should be explicitly modelled, including also the wind/PV power installed there. Alternative approaches include assuming fixed flows obtained from other studies or based on assumed market prices in neighboring regions. These approaches will error on the pessimistic side and should be mentioned clearly in the study conclusions.
- To capture the limitations from the transmission network, congestion and N-1 security can be included directly within UCED. To reduce the computational burden for large systems or where stochastic optimization is used, net transfer capacity, or iterative methods can be used. Also, transmission systems limitations can be modeled in other dedicated tools and the resulting limitations included as constraints within the UCED model. 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/PV case used as a basis for comparison and assumptions regarding the types of generation that wind/PV power will displace, especially if estimating integration costs. Just adding wind/PV power, or using a scenario with equivalent wind/PV energy, but with a perfectly flat profile, may result in impacts not entirely related to wind/PV 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/PV energy studied. We recommend that for higher wind/PV shares, a scope that acknowledges and/or includes new potential sources of flexibility be made.

Network Simulations

<u>Steady-state analyses</u>

- *Creating a number of credible power flow cases*: snapshots chosen should include critical situations regarding wind and solar power, such as periods with high non-synchronous generation (wind/solar) and import via HVDC. This is in addition to the peak load and low load situations traditionally studied. The correlation between demand, wind and solar production, specific to a particular system or region, should be taken into account. An evaluation of the snapshot's statistical relevance is beneficial as an input to the cost-effectiveness of implementing corrective actions—for example as part of a multi-year analysis. Moving towards probabilistic analysis, full year with cost benefit analysis is recommended for network reinforcement.
- *Deterministic steady-state security analysis*: in compliance with N and N-1 security criteria, power flow analyses are performed to identify transmission network bottlenecks (congestion), and to assess the system's ability to maintain the voltage profile.
- *Network loading (congestion) assessment*: network branch loadings should be determined for wind/solar generation and load combinations, across a year, both for normal and contingency (N-1) situations. Bottlenecks can be identified in a probabilistic manner, so that by analyzing the overload risk and the aggregated severity index, planners can identify whether bottlenecks should be considered severe or whether they can be solved (temporarily) via operational measures. A probabilistic approach allows uncertainty factors such as the forced outage of transmission equipment, generation units and wind and solar generation variability to be considered.
- *Time-series power flow and operation of discrete controllers*: reducing the number of online conventional power plants will also reduce the number of continuously acting automatic voltage regulators, unless the plants are converted to synchronous compensators. Wind and solar variability may require more frequent operation of discrete controllers, e.g., shunt reactors, with a detrimental effect on plant lifetime and the viability of such an approach.
    - Power transfer fluctuations on cross-border lines caused by the variable production of wind/PV power plants should be examined to help determine the steady-state cross-border transmission power margins (net transfer capacity, while taking into account wind/PV energy production).
- *Short circuit levels*: for high wind and solar shares of production, some synchronous generation will not be dispatched, which may lead to a reduction in the minimum short circuit level in some locations (the presence of wind and solar generation in other non-traditional locations may actually improve the fault level in those areas). This, in turn, may affect the power quality, voltage step changes after shunt switching and the operation of line commutated HVDC converters, leading to the mal-operation of protection systems.
- *Protection systems*: increased generation capacity at lower voltage levels may lead to reverse power flows from distribution buses (former load buses), such that correct operation of protection systems should be ensured.

Dynamic analyses

- *Selecting snapshot cases for analysis*: A wide range of wind share, solar share, and demand levels (recognizing the correlation between inputs) should be included to best understand system dynamic limits. The snapshots selected need not be the same as those chosen for steady-state power flow analysis. It is also important to set up the case carefully—not simply replacing the same volume of conventional generation online by the addition of wind/PV plant, as several (conventional) generators could be reducing their output but remain online. Understanding the new commitment and dispatch patterns with the addition of wind and solar is important and should be carefully considered when setting up the stability cases and interpreting the obtained results.

- *PV and wind turbine models:* Appropriate model complexity will depend on the study application. Using the short circuit ratio (SCR) to determine the strength of the system, guidelines for the proper models to be used in stability studies are provided: generic RMS models for *strong* systems; EMT models for *weak* systems; and manufacturer-specific detailed RMS models for systems of *intermediate* strength. Ideally, studies should be performed with different PV and wind turbine technologies, but often it is sufficient to utilizeutilise generic models that capture the minimum performance required in the connection code.

- *Model validation and verification:* Validation of all models (conventional generators, PV and wind turbine, and load) is important. PV and wind turbine models should recognize (evolving) technology capability and grid code requirements

- *System stability:* Different systems may experience totally different dynamic issues (e.g., frequency stability, voltage stability, or transient stability challenges), dependent on the underlying correlation between wind/PV production and system demand, the underlying flexibility and capabilities of the conventional generation portfolio, relative location of generation assets and major load centres, etc., implying that specific system studies may be required.

- *Wind turbine/PV controls*: Studies should recognize that wind turbine/PV controls, as part of a coordinated control strategy(s), may offer system advantages. VSC-HVDC can, to a certain extent, also be used for system stabilization.

- *(Dynamic) load modeling*: With increasing shares of wind and solar generation on the distribution network, and power systems becoming 'lighter' due to the displacement of conventional generation (reduced inertia), load characteristics will more strongly influence system performance. Existing load models should be reevaluated, including frequency and voltage sensitivities, and the time varying nature of the load composition, and hence the load models themselves, should be considered.

- *Transient stability analysis:*
    - It can be important to include the effect of protection devices for both network and converter-interfaced generating equipment; however, boiler/steam turbine models are not required. Protection relay settings should recognize changes in the dynamic response of the system, and respect any dynamic operating criteria (e.g., frequency variation range) adopted by the local TSO. The ability to ride through multiple voltage dips within a certain period may also need to be addressed.
    - Wind and solar generation can provide system support during voltage dips, and help to dampen oscillations, although the level of support provided is network sensitive, and the capability may also vary depending on the priority given to active or reactive power recovery. Proper representation of the impedance connecting the wind power plants is crucial within simulation studies.

- To mitigate any issues discovered, fast acting reactive power response devices during and following disturbances can be applied, e.g., installing FACTS devices, synchronous compensators, and/or requiring all wind plants and conventional generators to incorporate that specific capability.
- *Voltage stability studies:* At low wind/solar shares it is probably unnecessary to perform studies, as system stability is likely to be unaffected or even enhanced by the presence of wind turbines/PV panels. This argument is particularly true if the reactive power control capabilities of the wind turbines (PV) are deployed to manage voltage, and if they are connected at transmission level.
  - As conventional generation is displaced at higher shares of wind and solar, voltage security levels may be affected in certain locations, which may require requiring more detailed analysis.
- *Frequency stability studies:*
  - The fraction of generation participating in governor control is a good metric for the expected performance. The maneuverable capacity of such generation is also important, with resources providing significant incremental power in order for the frequency to return to its original working point. Particularly for larger systems, the self-regulating effect of the load can also ameliorate severe disturbances: simulation results can be sensitive to how the load is modeled.
  - Modeling 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. Reduced inertia at times of high non-synchronous (wind, PV and/or HVDC input) shares will alter the system response for both faults and contingencies, particularly for smaller power systems.
  - A reduced network representation may be sufficient, focusing on demand-generation imbalances and active power flows, with reduced consideration of voltage variations and reactive power requirements. However, underfrequency load shedding can provide system support during frequency drops, and proper representation of the frequency disconnection rules stipulated in the national Grid Codes is crucial for such studies.
  - Wind turbines can provide a fast frequency response, depending on their operating point, and PV plant can provide a similar response if their output has previously been curtailed. Fast-acting load response or storage may also be included.
  - Mitigation measures include disabling/replacing aspects of distribution connected protection schemes for wind plants, while 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 change of frequency should be reviewed.
  - It is important to set up the case carefully—not replacing the same amount of generation online as added wind/PV, as several generators can be reducing their output but still be online. Understanding the new commitment plus dispatch patterns with addition of wind and solar is important and should be used to set up the stability cases.
- *Small-signal stability studies:* Wind and solar generation do not generally introduce small-signal oscillatory modes, but as their presence may displace conventional generation (and associated power system stabilizers) and alter the magnitude and direction of transmission line power flows, it follows that small signal stability may be impacted.
- *Sub-synchronous oscillations*: Sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI) should be investigated as part of small-signal

stability analysis, particularly in relation to doubly fed (type 3) wind turbines. A range of mitigation measures including bypass filters, FACTS devices, auxiliary (damping) controls are available.

- *Common-mode fault events*: Network faults and/or loss of a major infeed can result in widespread voltage depressions and/or large frequency deviations and the common-mode tripping of local wind and solar generation. Consequently, the operation of associated protection systems may play a crucial role in determining system outcomes, requiring sophisticated modeling methods. Delayed active power recovery from grid code compliant generation following a widely seen network fault may similarly lead to a common-mode power reduction and frequency stability issues—voltage dip induced frequency dips.

Distribution grid analyses

- *Overlap and coordination with transmission grid studies:* The scope, tools and methodologies for distribution grid studies will continue to expand and develop. A major driver is the integration of wind and PV systems at the distribution level, which entails both challenges and opportunities for distribution grid planning and operation. Stronger coordination of transmission and distribution grid studies will be required with higher shares of wind/PV to access the full capabilities and flexibilities of distributed resources for the overall bulk power system.
- *Distribution grid reinforcement analysis*: A comprehensive catalogue of grid planning measures should be considered as part of the grid reinforcement analysis, i.e., grid optimization before grid reinforcement and before grid expansion. Based on available input data and the scope of the study, the analyses can either be performed using representative grid data or actual data, if available. For comprehensive system-wide distribution grid studies, a high degree of automation for data handling is required and recommended.
- *Grid losses analysis*: a detailed study of the grid losses for a certain number of representative distribution grids, combined with statistical analysis or data-driven methods, is recommended to recognize the large variation in the network characteristics of distribution grids. It is also essential to consider both the location and generation pattern of wind/PV when representing distribution grids, as they both have a significant impact on the grid losses. In order to partially validate the implemented model of the grid area, the energy flow in the studied grid area can be investigated in comparison with real measurement data available at transmission level bulk supply points.

Analyzing and Presenting the Results

- If the results show unexpectedly high and costly impacts of wind/PV 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 share of wind/PV, size and type of power system and the main assumptions and limitations arising from these.

The Future

Despite the presence of new resources with their underlying variability and uncertainty, it should be assured that the power system continues to operate with high level of reliability and security. Integration studies must strive for this. Integration study methodologies continue to

evolve and will benefit from the experiences of systems operating with large amounts of wind and solar energy. Recommendations for the main steps and methodologies to conduct integration studies will be updated as part of continuing international collaboration under IEA Wind TCP Task 25 and IEA PVPS TCP Task 14.

Recommendations on how to operate power systems in future are linked to policy and market development. Work that may influence future recommendations includes the following:

- Development of flexibility metrics and tools that can evaluate the flexibility needs of the power system and ways to achieve that flexibility, considering new sources like storage and energy system coupling (heat, power, transport, gas)
- 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 - and system value, with cost benefit analyses
- Knowledge about stability issues with very high-share wind/PV cases and in weak grids– as well as methodology for the emerging 100% renewables studies
- Studying how large amounts of wind power impact different market elements so that market integration strategies or alternative market designs can be recommended. It is not well-known how markets should be designed to incentivize flexibility and generation resource adequacy in systems with high wind energy shares or to enable effective use of wind/PV capabilities for power system support (for example, when running in curtailed mode).

List of Acronyms and Abbreviations

AC: alternating current
AGC: automatic generation control
AIGS: All Island Grid Study
ARMA: autoregressive-moving-average-model
AVR: automatic voltage regulator
CAES: compressed air energy storage
CCC: current commutated converter
CIGRE: Conseil International des Grands Réseaux Électriques
CIRED: Congrès International des Réseaux Électriques de Distribution
COPT: capacity outage probability table
DC: direct current
DLR: dynamic line rating
DR: demand response
DSM: demand side management
DSO: Distribution System Operator
EHV: extra high voltage
ELCC: effective load carrying capability
EMT: electromagnetic transient
ENTSO-E: European Network of Transmission System Operators for Electricity
EWITS: Eastern Wind Integration and Transmission Study
FACTS: flexible alternating current transmission systems
FOR: forced outage rates
FRT: fault-ride-through
GIS: Geographic Information System
GW: gigawatt
H_2O: water
HV: high voltage
HVDC: high-voltage direct current
ICT: information and communication technology
IEA PVPS: The International Energy Agency Technology Collaboration Programme for Co-operation in Photovoltaic Power Systems
IEA Wind: The International Energy Agency Technology Collaboration Programme 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
kWh: kilowatt-hour
LADF: line outage distribution factor
LCC: line commutated converter
LCOE: levelized cost energy
LOLE: loss of load expectation
LOLP: loss of load probability
LP: linear programming
LV: low voltage
MAE: mean absolute error
MILP: mixed integer linear programming
MIP: mixed integer programming
MISO: Minnesota Independent System Operator
MMC: modular multilevel converter

MW: megawatt
MWh: megawatt-hour
N-1 security: security is maintained when any one of the total number of possible faults occurs
NC RfG: network code requirement for generators
NERC: North American Electric Reliability Corporation
NOVA principle: grid optimization, before grid reinforcement, before grid expansion
nRMSE: normalized root mean square error
NTC: Net transfer capacities
NWP: numerical weather prediction
NYISO: New York Independent System Operator
PDF: probability density function
PINT: put in one at a time
PJM: Pennsylvania-New Jersey-Maryland Interconnection
PoC: point of connection
PSS: power system stabilizer
PTDF: power transmission distribution factor
PV: solar photovoltaic power
QSTS: quasi-static time-series
R&D: research and development
RES: Renewable energy sources
RMS: root mean square
RTTR: real time thermal rating
SCR: short circuit ratio
SCUC: security constrained unit commitment
SSCI: sub-synchoronous control interaction
SSTI: sub-synchoronous torsional interaction
SVC/STATCOM: static VAR compensator/static synchronous compensator
TOOT: take out one at a time
TSO: Transmission System Operator
TTCs: total transfer capacities
TYNDP: ten-year network development plan
UC: unit commitment
UCED: unit commitment and economic dispatch
UK: United Kingdom
USA: United States of America
VSC: voltage source converter
VG: variable generation
WWSIS: Western Wind and Solar Integration Study

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1 Introduction: What to Study

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Wind/PV power will introduce more variability and uncertainty into operating a power system due to the natural factors that generate wind/PV and the inability to perfectly predict them. To meet these challenges, 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. The feasibility of integrating wind/PV power is demonstrated through case studies that analyze the impacts on power systems: integration studies.

Recommendations for how to conduct wind/PV integration studies will depend on the share of wind/PV to be studied. As a metric for the share, this recommendations report uses the share of wind/PV electricity from annual electrical energy (i.e., gross demand). There is no standard practice regarding what share of wind/PV power in electric energy is considered low or high share (see also Müller and Vithayasrichareon 2017). How low share is defined depends on power system characteristics: 5% may be considered a high share in some systems, while 10% can still be considered moderate share for more flexible systems. High shares generally refer to shares exceeding 20% of gross demand. For solar PV, high share may be reached earlier than for wind.

This recommendations report begins by outlining wind/PV integration issues, or the impacts that wind/PV may have on power systems. From there, the phases of a complete integration study are illustrated as a flow chart. Then Sections 2 through 7 describe activities related to the main boxes of the flow chart in Figure 2: Input data, portfolio development and system management, capacity value, production cost simulations and flexibility assessment, network simulations, and analyzing and interpreting results. Each section addresses issues that are relevant to wind/PV integration with a checklist of recommendations. The report concludes with a summary of the recommendations and suggestions for future work. The report is about data and methodology—for results of integration studies, the reader can refer to summary reports (Holttinen et al. 2009, 2013, 2016; PVPS 2014 and 2017).

The current report is the second edition of the recommended practices published by the IEA Wind TCP (Holttinen (Ed) 2013). In the recommendations, solar PV has been added and distribution networks have been addressed. Especially for PV—and also in part for wind—a high share of capacity is connected to the distribution level.

1.1 What to Study: Overview of Wind/PV Integration Issues

Before integrating new power plants in a power system, it is necessary to assess the grid adequacy in long time scales and implications to system balancing and dynamic stability in shorter time scales. Implementing wind/PV power has impacts on power system management, economics, and efficiency. The optimal conventional generation mix may change at higher shares of wind and solar. 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 resolutions, as well as both system-wide and local effects (see Figure 1). The grid integration challenges in the distribution level usually have a stronger focus on local or regional effects of wind/PV deployment, rather than the transmission level and system-wide issues.
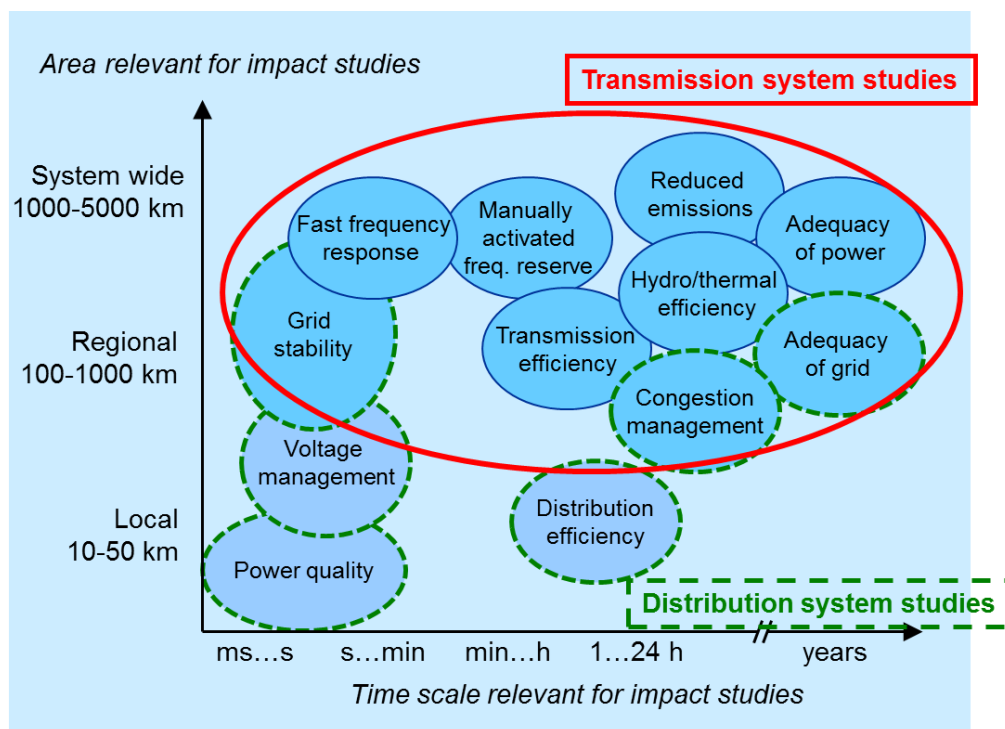
Figure 1. Impacts of wind/PV power on power systems, divided in different time scales and geographic width of area relevant for the studies. The red line encircles those more regional scale, transmission and power system level issues. The green dotted lines are relevant for more local, distribution system issues. Transmission and distribution efficiency refers to grid losses and hydro/thermal efficiency refers to losses in generation.

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/PV power. Market design also affects the efficiency and adequacy of power and transmission.

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

The three main issues described below could be studied independently. They cover different time horizons but the main focus for integration studies is long term planning. For example, balancing addresses the short term operational impacts but can be incorporated in the long-term planning in a tool such as production cost models.

1.1.1 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/PV 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/PV power distributed (dispersed) to a large, system-wide area will be combined with other uncertainties experienced by the power system, e.g., 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/PV variability (the smoothing effect depends on how concentrated or well dispersed wind/PV power is sited).

Efficiency and unit commitment (UC) (time scale: hours to days): Here the issue is how the conventional capacity is chosen to run and how the variations and prediction errors of wind/PV 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/PV and minimum load need to be addressed. Analyzing and developing methods of incorporating wind/PV into existing planning tools is important to correctly take into account wind/PV uncertainties and existing constraints and flexibilities in the system. The simulation results give insight into the technical impacts of wind/PV power, as well as the (technical) costs involved.

1.1.2 Capacity Value and Adequacy of Power Generation

For assessing the adequacy of power generation, the time scale associated is several years. Here the issue is about total supply available during peak load situations. Generation capacity adequacy is associated with static/steady state conditions of the system, also referred as the margin of the system. The estimation of the required generation capacity 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).

The proper assessment of wind/PV power's aggregate capacity value must take into account the effect of geographical dispersion. It will need many years of data to capture possible critical situations with wind/PV generation during peak demand hours.

1.1.3 Network Adequacy and Stability

Wind and PV affect the power flow in the network (time scale hours). The impacts of wind power on network depend on the location of wind and solar power plants relative to the load and the correlation between wind/PV generation and load consumption. They may change the power flow direction or reduce/increase power losses and affect bottleneck situations. There are a variety of means to maximize the use of existing network infrastructure. However, grid reinforcement is often necessary to maintain network adequacy when adding significant levels of wind and PV capacity. Economic planning of transmission networks with wind and solar need to capture 8,760 hours of power flow, along with cost and benefit analyses. Transmission capacity between areas is also an enabler to integration

Assessing the impacts of wind/PV generation on power system dynamics (time scale: seconds) will be important at higher shares. The possibilities to support the system in normal and system fault situations include voltage and power control and fault ride through capability, and control capabilities of wind/PV power plants should be recognized within any study. The siting of wind/PV power plants relative to load centers will have some influence on this issue as well. When significant amounts of wind/PV generation are interconnected to the distribution system, the voltage stability assessment should include the expected diversity of voltage profiles, as this may impact the power system's response to faults and other abnormal conditions.

1.2 Contents of a Wind/PV Integration Study

A complete integration study, including all the aforementioned issues, is presented as a flow chart in Figure 2 that illustrates an overview of what a complete integration study should contain (Figure 2). 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. Often studies are conducted in phases; for example, studies can first include more local issues before evolving to study more system-wide issues (see also IEA (2017) showing more details for the first 1-5% shares of wind and solar).
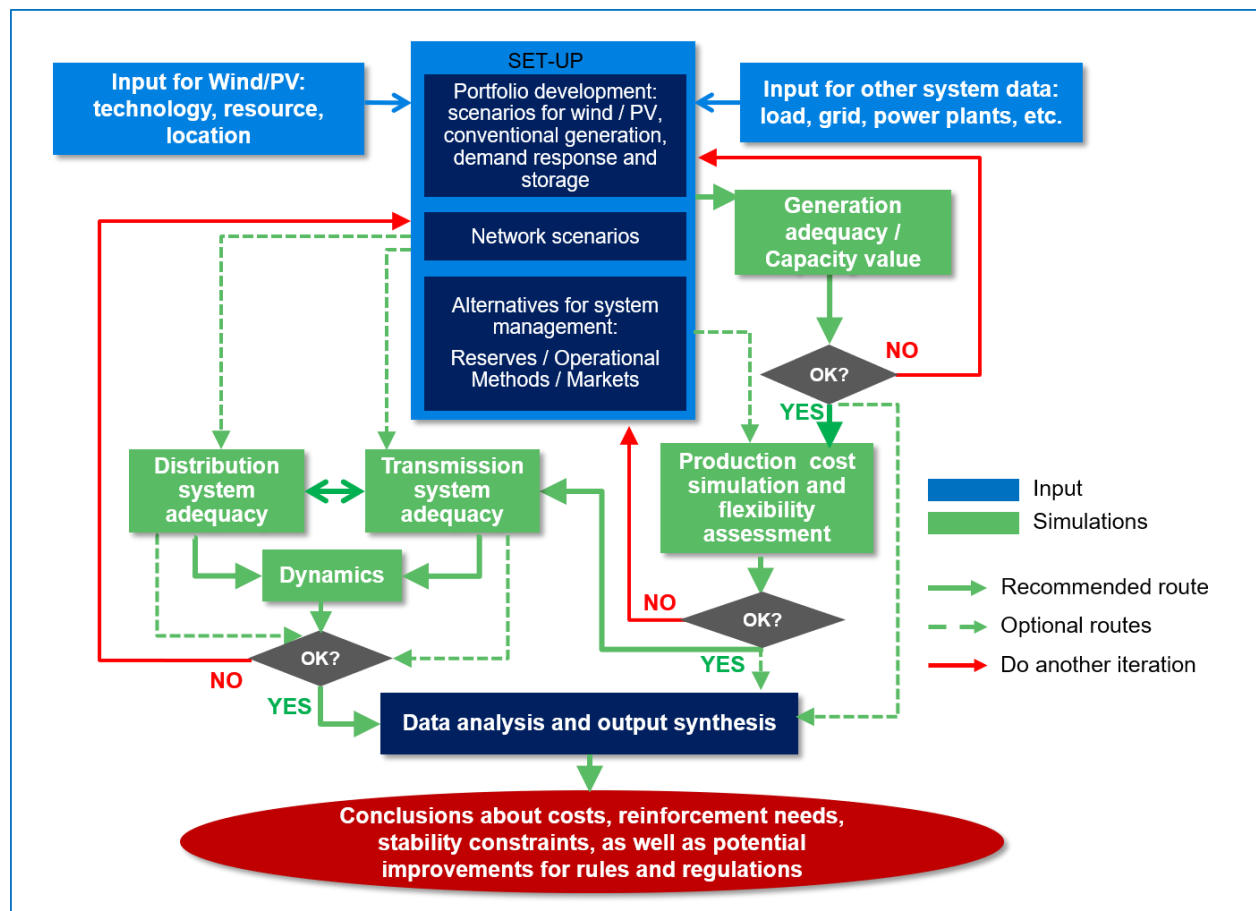
Figure 2. Wind/PV integration study components; flow chart showing a recommended route with iteration loops and possible routes when not all components are studied

A wind/PV integration study usually begins with choosing what to study (which of the green simulation boxes will be performed and which will be omitted) and which geographical system to study (e.g., an electrical footprint including a subset of the system, or the entire synchronous system). Analysis of an entire synchronous system can characterize 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 modeling of interactions between the boundaries of the study area and the remaining synchronous system.

Portfolio development needs to establish whether current or future system is studied, 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/PV power is added to the system—whether by replacing existing generation, adding wind/PV power to the existing system, or developing optimized portfolios for both scenarios.

Changes in system management may need to be made from the start to accommodate large amounts of wind/PV 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 may also have to be changed to a more holistic and cost-effective one.

Input data that characterizes wind/PV power, as well as the underlying power system, are required to enable relevant simulations of the study (the top two blue boxes in Figure 2).

Wind/PV integration studies usually involve investigations of transmission and/or distribution grid (like power flow, voltage profile, short-circuit power), calculations of the generation capacity needed to meet resource adequacy requirements in the peak load situations, and simulations of the operation of power plants in the system (represented by the green simulation boxes in Figure 2) More detailed stability simulations and flexibility assessment are necessary when studying higher shares of wind/PV power.

Reliability constraints from transmission or generation capacity adequacy or reserve margins will require iteration on the initial results to adjust the inputs and set-up of study. Installed capacity of the remaining power plants (i.e., the generation portfolio) or the transmission/distribution grid can be changed or remedial actions to the network or operational methods of system management can be applied.

Analyzing and interpreting results is the last phase in a study. Usually the studies try to quantify wind/PV impacts by comparing simulation results from no (or little) wind/PV with future higher amounts of wind/PV power. Some studies try to estimate integration costs for the system. The benefits of wind/PV power to the system can also be quantified, and they should be larger to justify/underpin the wind/PV energy targets.

1.3 Phases of Integration Studies

Depending on the wind/PV shares studied and the power system issues, some components of the flow chart can be omitted.

In many countries, PV in particular tends to have a high share of capacity connected at the distribution level.[3] The grid integration challenges at the distribution level focus primarily on the local or regional effects of wind/PV deployment, such as local voltage rise or overloading

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[3] The National Survey Reports by the IEA PVPS program (website: http://www.iea-pvps.org/?id=93) provide a detailed overview on the installed PV capacity and voltage level of interconnection for several countries. For example, countries such as Australia, France, Italy, Japan and Germany are characterized by a high share of PV capacity connected at the distribution level. Nevertheless, also for some countries such as China a major share of PV capacity is connected to the transmission level.

of grid assets. Grid integration challenges with distributed PV from (Stetz et al. 2014) can usually also be applied to distribution grid-connected wind parks (**Figure 3**):

- *Phase 1:* Low to medium PV/wind share in a few distribution grids—local consumption still exceeds local generation (uni-directional distribution grids). Distributed PV/wind may cause local over-voltage or over-loading issues. Distributed PV/wind have no or low impact on the transmission system operation. In Phase 1, distributed PV plays usually a passive role; for example, generators provide maximum active power feed-in.

- *Phase 2:* High PV/wind share in a few distribution grids—local generation can exceed local consumption (bi-directional distribution grids). A major challenge of the DSO is the increase of the hosting capacity of the distribution grids for distributed energy resources. From a transmission perspective, the necessity of re-dispatches or congestion management can especially increase in regions with high PV/wind deployment. In Phase 2, distributed PV systems are usually required to provide additional ancillary services (for example, reactive power control for voltage management or active power curtailment for congestion management).

- *Phase 3:* High PV/wind share in many distribution grids and a system-wide high PV/wind share. Major PV/wind integration challenges are determined especially for the transmission level, such as voltage stability issues, balancing issues, black start issues and re-coordination of protection settings. In Phase 3, PV is an integral part of the power system and also is required to provide additional ancillary services for the transmission system operation (e.g., balancing challenge).
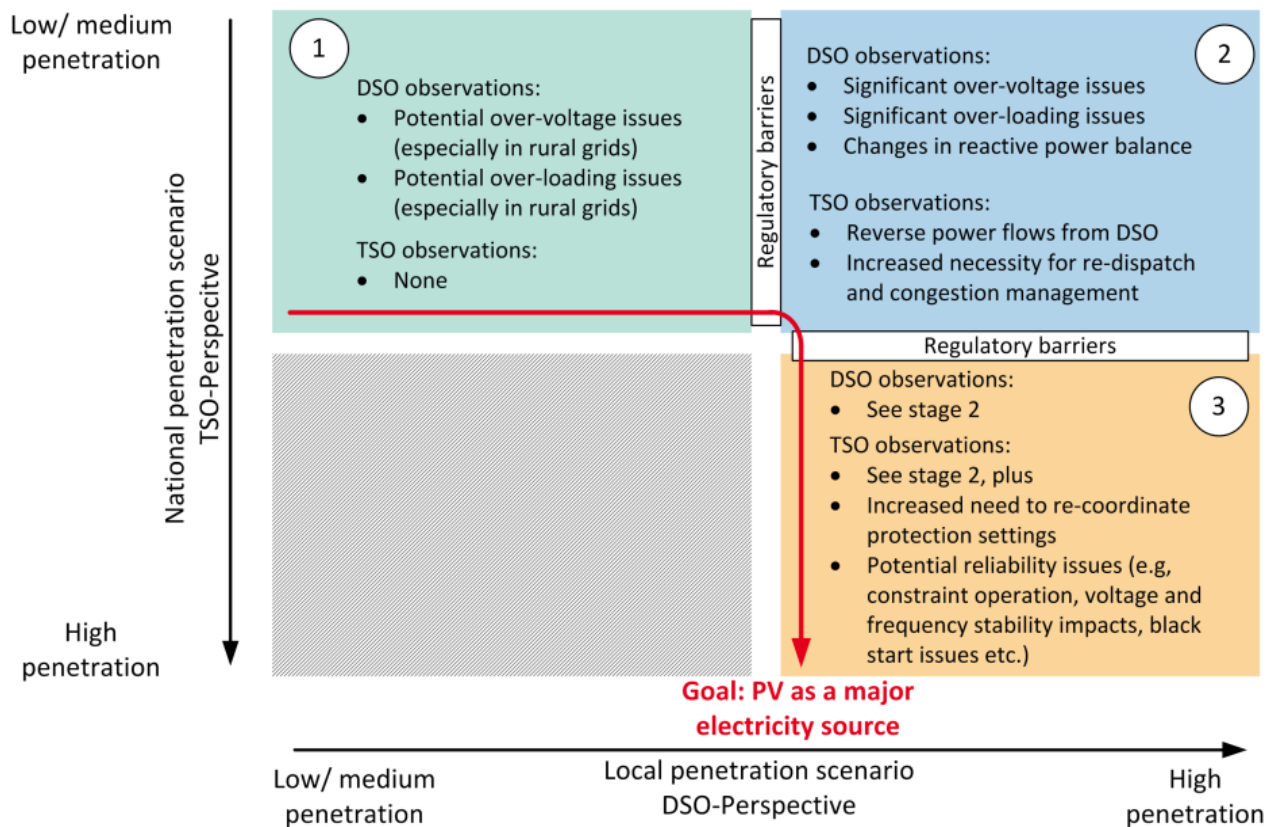
Figure 3. PV share and challenges for the electrical power system (Stetz et al. 2014)

Going from local to system wide studies, an example of phases of studies is given in the IEA Manual for policy makers, *Getting Wind and Sun onto the Grid* (Müller and Vithayasrichareon 2017). Four phases are described; phases 1 and 2 do not yet require an integration study, and phases 3 and 4 include increasing detail captured in studies (Table 1).

Table 1. Phases of a variable renewable energy (VRE) integration study (Source: Müller and Vithayasrichareon 2017)

Phase	Description
1	VRE capacity is not relevant at the all-system level
2	VRE capacity becomes noticeable to the system operator
3	Flexibility becomes relevant with greater swings in the supply/demand balance
4	Stability becomes relevant. VRE capacity covers nearly 100% of demand at certain times
5	Structural surpluses emerge; electrification of other sectors becomes relevant
6	Bridging seasonal deficit periods and supplying non-electricity applications; seasonal storage and synthetic fuels

For power system wide studies, examples of studying a system with increasing detail can be seen in the case of Ireland in All-Island Grid Study (AIGS 2008), Facilitation of Renewables

Studies (Eirgrid and SONI 2010) and the Delivering a Secure Sustainable Electricity System - DS3 programme (Eirgrid 2015). Another example is the US Western Interconnect, WWSIS phases 1 (WWSIS 2010), 2 (Lew et al. 2012) and 3 (Miller et al. 2014). For integration studies, phases can be defined as:

- *Phase 1:* At lower shares, the main interests are the impact of wind/PV power on the other power plants and the need to upgrade the transmission network (production cost simulation and network adequacy). Impacts to reserve requirements may also be addressed.

- *Phase 2:* For higher shares, generation capacity adequacy and capacity value of wind/PV are often studied, and a more detailed flexibility assessment is useful. Some stability issues (e.g., low inertia linking to frequency stability, voltage stability in some locations) may also be seen. Portfolio development coupled with transmission and distribution network development will also need to be addressed in greater detail.

- *Phase 3:* At even higher shares, which can lead to periods of very high instantaneous wind/PV production, issues may arise in power system stability, network protection, harmonics and other technical areas. Where problems are identified, a wide range of mitigation measures can be considered, particularly in operations (e.g., demand side response, dynamic line rating, modified grid codes, new ancillary services, control room software tools) and planning timeframes (e.g., AC and DC network upgrades, FACTS and network control devices, flexible generation, energy storage).

1.4   Enablers of Wind/PV Integration

Increased variability and uncertainty due to wind/PV 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 need 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/PV power plants can also be used to provide flexibility; however, reducing the possible output level of power plants 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 4 shows a general view of flexibility options and their relative cost effectiveness. Smart (actively controlled) Grids can enable the use of demand side management (DSM) and take advantage of the distributed generation flexibility.
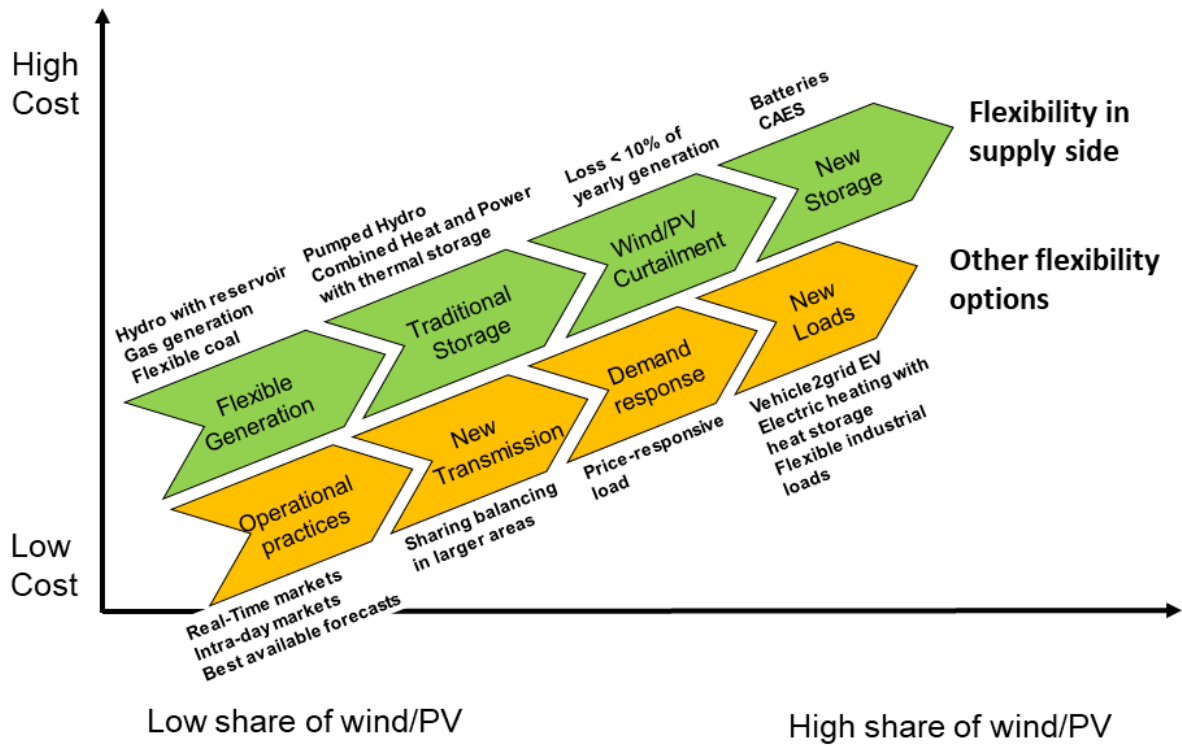
**Figure 4. Cost of increased flexibility in power systems, general trend
(Original source: UWIG)**

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2 Input Data

This chapter describes all the data required in a wind/PV integration study, including generation resources, load and grid. These are illustrated in the outer blue input boxes in the wind/PV integration study components flow chart (Figure 5).
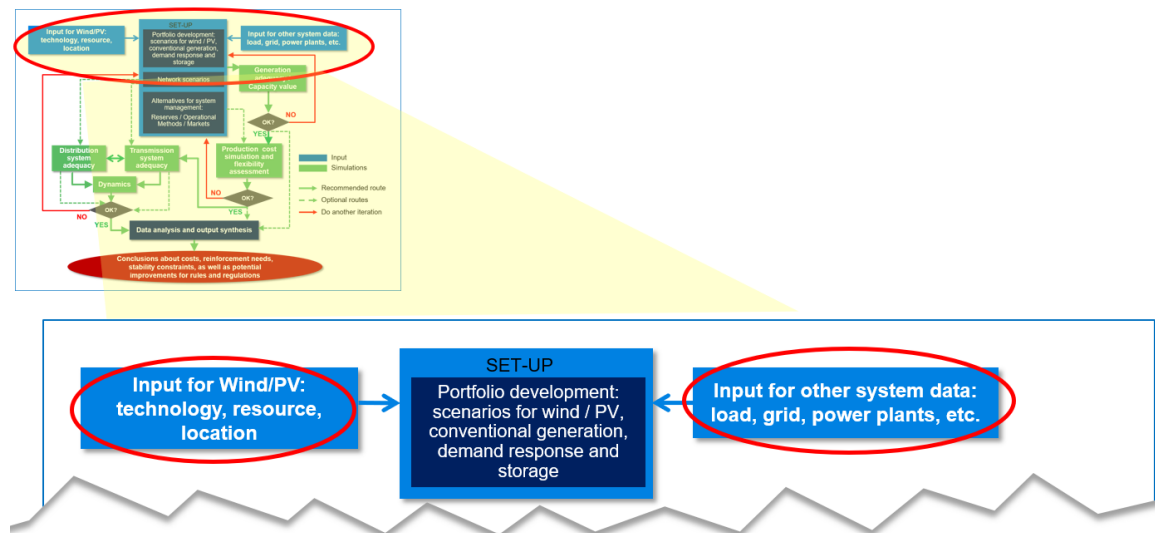
Figure 5. Wind/PV integration study components: inputs needed for a wind/PV integration study

Wind/PV integration studies require data on not only the wind/PV power, but also other power plants, loads, and the transmission and/or distribution grid topology and characteristics. When the integration study is aimed at estimating the potential impacts of large amounts of wind/PV power in a future year, the assumptions regarding all of these data will impact the results considerably.

Different types and volumes of data will be needed in the different types of simulations that could comprise a study. For example, in some unit commitment and dispatch modeling the transmission grid can be represented by only net transfer capacities between balancing areas restricting transmission flow (recommendations are summarized in Table 3).

2.1 Wind and PV Data

Jan Dobschinski, Hannele Holttinen, Markus Kraiczy, Barry Mather, Ana Estanqueiro

Data for wind and solar PV power production should capture the generation capability, with characteristics of the variability and uncertainty. These can be used to extrapolate the characteristics of future anticipated wind and solar power plants. The detail of the data as well as the important characteristics to be considered will vary according to the simulation (see Table 3 and Table 3).

In general, the basic data requirements for wind and solar PV as input in integration studies are similar. It is evident that the aggregation of dispersed wind/PV power plants in a larger area leads to a reduction of variability, and also of uncertainty, i.e. the sum of the individual

production and forecast error time series leads to smoothed aggregated time series (Dobschinski et al. 2014). This effect is generally based on the stochastic nature of wind and solar power production leading to local differences in the weather situation and predictability. The greater the independence of the power production of several locations the greater is the spatial smoothing impact when aggregating these locations.

Combining realistic wind and PV power time series leads to a smoothed variability and reduced global forecast errors relative to the capacity. Often wind and PV forecast errors balance each other because individual error contributions can be either positive or negative. However, in extreme situations, wind and PV forecast errors could add on top of each other.

The accurate modeling of variability and uncertainty in the studied area is the main challenge for wind and solar PV. Errors in the modeling of variability and uncertainty can be key drivers of unrealistic results within the studies. Extreme ramps and forecast errors should be captured in a realistic way, since a few time steps with large errors can drive overall results.

It is necessary that both wind and PV time series are based on co-incident weather data, to represent realistic conditions. These data should also be co-incident with other weather-dependent data like demand and hydro power. It is recommended to base the input data of an integration study on co-incident weather data such as wind, solar radiation, temperature, and rain.

2.1.1 Generation Time Series

Jan Dobschinski, Barry Mather, Hannele Holttinen, Ana Estanqueiro

Wind/solar power production time series of a certain length and of a certain temporal and spatial resolution is needed in any wind/solar integration study of future power plants. There will be different requirements on data sets for different studies (Table 2).

Table 2. Requirements for generation time series input data of wind power/PV generation for integration studies

	Capacity Value/ Power (resource) Adequacy	Unit Commitment and Economic Dispatch (UCED) Including Reserve Requirements
Temporal Resolution	Typically, hourly data is enough	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/PV output during peak load situations than to incorporate spatial smoothing effect of variability.	System-wide time series, incorporating spatial smoothing effects
Length of Investigation Period	Long time series of 6–10 years especially for wind power, more than 10 years improves the assessment catching extreme low winds during peak loads	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 Synchronization	Coincident wind. PV and load time series, and if applicable, also of other weather-dependent generation	Coincident wind, PV and load time series. If applicable, also coincident time series of other weather-dependent generation

Capacity value represents an equivalent capacity of the resource providing to the desired level of reliability of the system. It captures the contribution of the wind and solar plants to generation capacity adequacy (also called 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, PV and load is a key factor for this type of study, coincident time series are crucial. Especially for wind power, 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 share of wind energy on the system. For Ireland, seven years was needed to produce robust results (10 years of data in Hasche et al. 2011). For Finland, 14 years was needed and a ±10% uncertainty remained in results (from 35 years of data, Milligan et al. 2016). In France, several decades of data were needed to capture all statistics and extremes in the data (EdF 2015). 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 unit commitment and dispatch (UCED) simulations the required temporal resolution depends on the model. The minimum requirement to catch wind and PV variability is using chronological, hourly generation data. However, 10- to 15-minute data will capture more variability impacts (Melhorn and Flynn 2015) and may be useful especially for PV to capture

the morning and evening ramps. It is important to have enough power generation measurements from wind and solar power plant sites to cover the dispatch area. The spatial resolution of wind datasets may need to be higher than for PV. This is due to PV's high correlation to the temporally predictable solar resource and wind's potentially varied output over even relatively small regions. The generation time series of wind and PV have to be co-incident with load data (and, if it forms a significant part of the generation mix, to hydro power 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 (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 operating reserve requirements, (also as part of unit commitment and dispatch simulations) capturing larger possible forecast errors is important. 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 multiple years to have better representation and accuracy (Dobschinski et al. 2010). With respect to dynamic reserve settings you have to differentiate between the type of probabilistic forecast that is applied. Using a quantile forecast model that is based on a historical training period with already observed forecast error data it is also recommended to consider error time series of multiple years. If you use an ensemble prediction system (EPS) instead, you have to guarantee that the EPS is reliable. The advantage of a reliable EPS is the ability to forecast extreme events (also error events) that have not been predicted in the last years (Dobschinski 2017). Nevertheless, the modelling of extreme forecast errors considering also potential forecast improvements within the next decades remain a big challenge and a high uncertainty within integration studies. Therefore, it is recommended to perform a sensitivity analysis to be able to estimate the impact of the used forecast error simulation on the final results.

Usually the short-term variability over a few seconds up to a minute time scale is generally independent for each wind or solar plant—resulting in the nearly complete cancellation of such variability within 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- to 60-minute variability. One such method is described in King et al. (2012).

For power flow analysis, the spatial distribution should be that of the grid under investigation, i.e., the nodes of a transmission or distribution grid. It is crucial to choose a realistic future distribution of power plants connected to these nodes (Wolff et al. 2007). Since power flow calculations are rather time-consuming, usually snapshots (several single points in time) are considered. Ideally the extreme cases are taken from a very long time series (from wind/PV/load/other generation worst case combination). In cases where acquiring such data is not possible, different extreme situations of wind power generation, other generation, and load are combined. They are from different points in time, which means that they should be chosen such that they could realistically occur simultaneously. Using nameplate data for the Wind/PV generators can lead to an over-estimation of the maximum PV/Wind generation scenario. For the quantification of the probability of extreme load events, the frequency of occurrence is necessary for the situations used.

For a detailed time-series analysis at the distribution system level (e.g., variability analysis for voltage regulation), the wind and PV data requirements are usually high, for both spatial resolution (d < 10 km) and temporal resolution (t ≤ 10 min). As such data is usually not available for most distribution integration studies, characteristic generation profiles for generators and loads are typically considered. This approach is suitable for the assessment and comparison of different voltage regulation strategies and components (e.g., PV reactive power

control, on-load-tap changers, etc.), but it often does not appropriately represent the smoothing impact of wind/PV generation across the footprint of the distribution system being studied.

For system stability studies time series calculations are rarely performed and mostly the wind input is kept constant for each calculation's case (see Section 2.1.3).

Smoothing impact: Analysis has shown that the variability of wind and solar power output declines on a per-unit basis as the level of installed capacity increases. Representative wind/PV data for an integration study should incorporate the variability and smoothing impact of the system area with anticipated, dispersed wind/PV sites because variability and uncertainty are key drivers of the study results. Siting of the power plants in the most realistic manner is also important for the transmission studies to model how they are located relative to consumption centers. The impact of the spatial dispersion of the wind/PV sources on the smoothing of the overall variable generation should be taken into account, as a carefully planned wind/PV generation mix will contribute positively to minimize the overall variability of the generation.

The wind at one location is only partially correlated with nearby turbines or wind plants. The same applies for PV when operating on a partly cloudy day when a single plant has high variability. Correlation is generally smallest at the shortest time scales, increasing somewhat at longer time intervals. The aggregation benefit, or smoothing effect, can be seen in less steep ramps as well as lower peaks of generation, and the aggregated generation does not have as many close to 0 hours.

General information about the smoothing effect of large-scale wind power:
- Per-unit variability of wind generation decreases when there are more wind power plants dispersed 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 dispersed wind power.
- The size of the area and the way wind power plants are dispersed 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 land-based wind power.

General information about the smoothing effect of large-scale solar power:
- For solar, the main variability due to daily pattern is easier to catch
- The variability due to partly cloudy weather will smooth out with wider area deployment, and the daily generation curve will resemble a bell curve.
- The larger the area, the smoother the morning and evening ramps of solar are.

In general, data can be obtained from measurements and numerical model output data.

Using real generation time series

Ideally, one would have actual high-resolution wind and solar generation data from all sites included in the study, and those would be input to the integration study. Using existing

generation data will clearly provide realistic smoothing characteristics and can be applied for studies with lower shares of wind and/or PV. However, for capturing sites that are outside the data, and new higher turbines, or larger share of offshore wind, or different share of roof-top and large solar power plants, this approach has caveats. For most countries, only some wind/PV power plant data and regional data are available.

Validation and cleaning of the measured time series data is a necessary step because of erroneous data values impacting the results of the studies. Often problems in data show as artificial peaks in the data, for example suddenly a 0 in between two higher numbers. In historical measured generation data there may be aspects other than wind or solar related variability included, such as curtailment, planned or unplanned maintenance, or self-consumption that would need to be taken out when using the data to represent future system operations.

The regional data available for many countries (e.g., Germany) are up-scaled values from measured data, based on representative wind and PV power plants. It is worth noting that such up-scaled production time-series data may have considerable errors compared to the feed-in of real-time production data (this is particularly likely for PV). A single small cloud over a representative PV power plant with a high share of the regional PV installations could lead to a reduced estimate of regional PV power production, when in fact most of the region has little cloud cover. Compared to large-scale and often homogenous wind fields, the wide-ranging patterns of potential regional cloud cover (e.g., many types of partially cloudy conditions) present significant challenges for the accuracy of upscaling algorithms.

Aggregations of all wind and solar power measurements are often only later available. With respect to the millions of PV panels it is worth to note that there are still missing measurements and other artefacts within the data that could not be considered entirety.

If measured power production data is used, the wind/PV energy share 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. The same applies for PV data on partly cloudy days, when the variability of a single plant is high. If the data already contain enough sites and number of turbines/panels 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 behavior 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. If existing data is available covering an area as large as anticipated and have dispersed data that incorporates the smoothing effect in variability, it can be used as an approximation. There are also rough methods that are based on existing production time series and a simple scaling to the new locations. The advantage is that these approaches rely on real data representing realistic weather conditions and power production characteristics. But there are also not negligible disadvantages. These rough models do not consider the local weather situations in a right way and they base on the assumption that there is no improvement in technology. On the other hand, there are detailed methods

considering future power curves, shadow effects and other relevant physical descriptions of the transformation process.

Using simulated generation time series

If the wind and PV generation 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 for wind and either satellite and/or NWP data for solar. Using model data for wind can capture larger areas and better mimic future scenarios of sites. However, measurements still play a crucial role in validating and improving the models and determining parameters used in the simulations.

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

NWP data may have caveats in representing the overall wind power production of the area correctly. For example, real wind power generation data from several sites still shows more smoothing effect than model data has shown (Holttinen et al. 2011). However, model data is improving. It is noteworthy that an increased spatial resolution within the NWP computational grid leads to a higher variability in the output data. Therefore, it is advantageous to use NWP with a spatial resolution higher than 5 km. NWP data of coarse models are not recommended for integration studies. When using model data for wind, 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 6 for hourly variation and in Figure 7 for 10-minute variations. The probability distribution of variability (P(t)-P(t-1)) also has to include a correct frequency of extreme variations (ramps).

Data is usually needed on an hourly basis. Most NWPs have a time resolution of 1h. Interpolation methods have to consider a correct variability within the hour and in space (correlation to nearby locations, ramps, etc.). 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 hypothesized wind plants.

When data is simulated for future sites where measurement data does not currently exist, it is best if datasets for all weather-related generation and load are generated from the same numerical weather prediction model (NWP) runs. This ensures that the physics of the atmosphere is consistent for wind, solar, hydro, and load, and helps to avoid erroneous ramps in power output that may arise from ad hoc time series creation methods (Delenne et al. 2015).
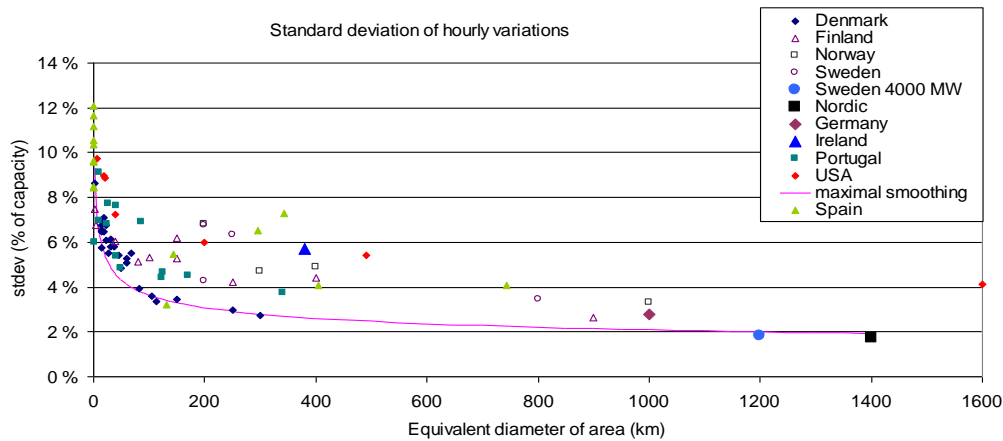
Figure 6. Indication of smoothing effect in the data, from standard deviation of the time series of hourly variations of wind power production; the size of the area is estimated as equivalent to the diameter if the area were a circle (Source: Holttinen et al. 2009)
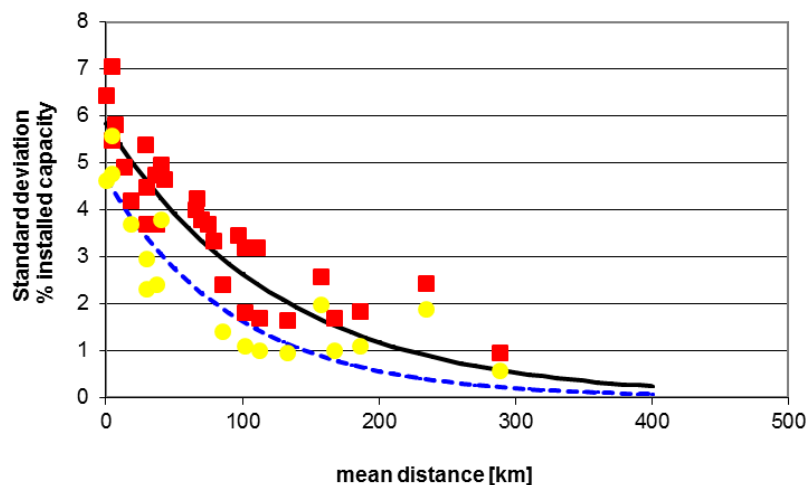
Figure 7. Standard deviation in percent of installed capacity for 10-minute (circles), 30-minute (boxes), 10-minute-fitted (dashed), and 30-minute-fitted (continuous line) change of total wind power as a function of mean distance between all wind power stations (Söder et al. 2012). Mean distance is calculated from a representative rectangle covering the area of the wind power plants.

2.1.2 Forecast Time Series

Jan Dobschinski, Bri-Mathias Hodge, Hannele Holttinen

Forecast errors for wind and solar power are relevant for balancing studies—UCED and reserve requirements—but are not currently utilized for grid simulations and do not impact the capacity value estimates significantly.

Forecasts for wind and solar use similar sources (weather models). It is important to use data from state-of-the-art forecasts, as a simple forecast will overestimate the uncertainty and impact the results of integration studies. Forecasts for the appropriate horizon should be used; the correct horizon depends on the operational practices and market requirements of the area under study. Considering the correct time horizon is important because of the forecast accuracy improvements seen as the forecasting horizon decreases, as shown in Figure 8.
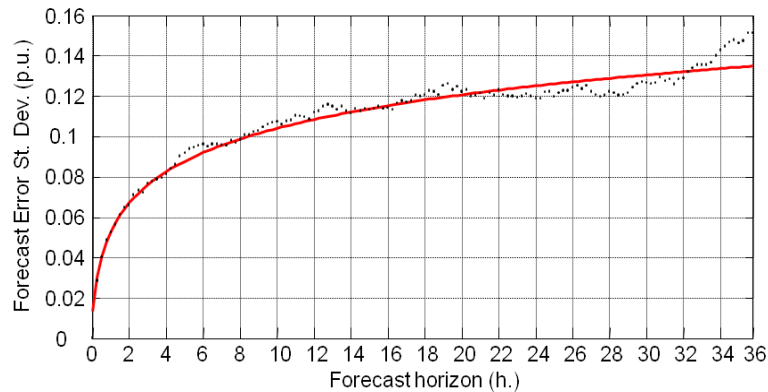
Figure 8. Normalized standard deviation of wind power forecast error for 12 GW of installed capacity versus forecast horizon (Source: Gibescu et al. 2009). Solid line is a curve fitting

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.

For wind power plants the average root mean square error for a 3-hour forecast for single wind power plants of 4.5–300 MW (nominal power) in Germany is 8.5% normalized to installed capacity (nRMSE). For the whole German wind power generation (3,908 MW mean generation), the nRMSE of a 3-hour forecast is approximately 3.1% (Dobschinski 2014).

For solar PV, the mean absolute error (MAE) of day-ahead forecasts of single plants is about 19% of capacity and reduces down to about 4% for system-wide aggregations. With respect to shorter lead times, the integration of recent PV measurements leads to further error reductions. For example, the two-hour forecast performance for aggregated 4.4 GW of PV in Spain is about 1.5%-2% of capacity (Tuohy et al. 2015).

As forecast accuracy is steadily improving (see for example Garcia Casado 2013), existing forecast data will overestimate future uncertainty of wind/PV power. Thus, assessment of future impacts due to wind/PV means simulating the forecast errors to get the uncertainty due to wind/PV power. These errors depend on the quality of the prediction system and the analyzed forecast horizon, which also illustrates the importance of reducing large forecast errors by optimizing forecast tools. Forecast error reduction needs to be estimated to the extent realistic in future generation scenarios. It is recommended to differentiate between estimations of future forecast improvement for average errors and extreme errors. Improvements of the rare extreme errors are much more difficult than improving average error scores.

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 9 example for wind power). Characterizing the rare events

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. Oftentimes, the "clear-sky" pattern of solar power output is used for simulating solar forecast data. This can have implications on, for example, short-term (hour-ahead) forecasts for integration studies. While for wind they often rely on the persistence method, for solar power a modified "persistence of cloudiness" method should be adopted to account for the diurnal patterns that are known *a priori*.

For the operational domain (short-term reliability assessment), wind and solar power as well as load uncertainties are provided by a probabilistic forecasting system, which allows a dynamic characterization of the uncertainties. If only the wind/PV 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).
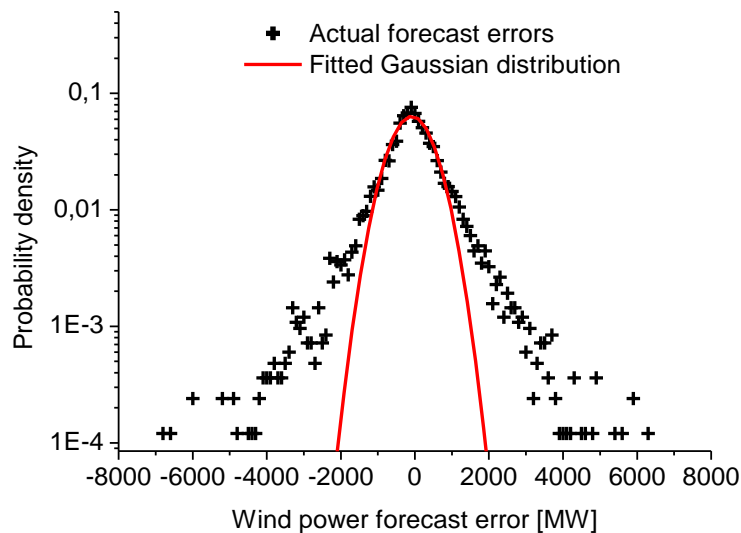
Figure 9. Larger forecast errors are more probable than a normal distribution would estimate (Source: Lange et al. 2006)
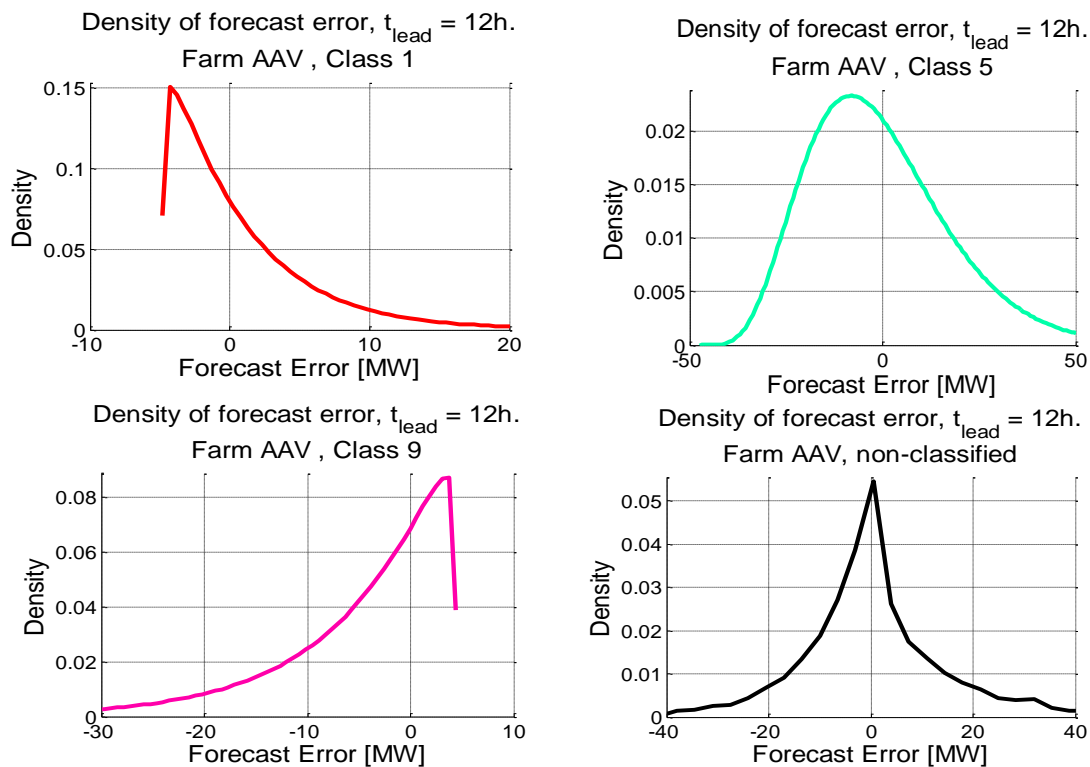
Figure 10. Forecast error distributions for different generation levels (top left for low forecasted generation, top right for medium generation level and bottom left for high generation). The bottom right graph corresponds to the case with all the data (no classification with respect to the generation level) (Menemenlis et al. 2012).

For UCED studies, a time series of the forecast error along with the generation data are needed. For historical data taken from forecasts performed in the past, the challenge is to get the future forecast error right taking into account improvements in forecast accuracy—also if a more dispersed and larger area will be used. A dedicated forecast system can be set up to produce the forecasts for the data set needed. If this is not possible, simulated forecast error data have to be used. Simulation of forecasts is not trivial. Spatial dependencies depend on the forecasting horizon, resulting in complex modeling.

Forecast error distributions can be used to form the time series. The error distributions for different situations can vary greatly (e.g., by time of day, delay-time and period of the year or for specific meteorological conditions). These distributions, taking into account that large errors are more frequent than in a Gaussian normal distribution, are band-limited and have fat tails capturing the rare events (Figure 9). Moreover, they depend on wind generation level (Figure 10). 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 summarized in Menemenlis et al. (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.

Where uncertainty is modeled using stochastic optimization, time series may take the form of a stochastic tree, representing possible future scenarios of system demand and wind/PV production. It is often desirable to use historical production time series for a number of historical years to capture the annual variability in wind/PV production.

2.1.3 Wind and Solar Power Plant Capabilities

Nicolaos Cutululis, Ana Estanqueiro

System integration studies need to take into account the relevant control features that enable wind and solar power plants to provide a response according to the power system needs for voltage and frequency control and stability. These control features are part of specific wind turbine and solar PV 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 requirements). 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
- For Unit commitment and Economic dispatch and reserves:
  − Active Power Frequency Response (automatically responding reserves)
  − Balancing power (manually responding reserves or balancing/real-time market operation)

Depending on the nature of the analysis, the 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, voltage/reactive power controls, and fast frequency response). The model complexity will depend on the study application (Flynn et al. 2017; Yamashita et al. 2018).

Solar PV is often installed in smaller capacities, more likely to be connected at lower voltage levels, and more dispersed than wind power. New wind power plants on the other hand typically connect at higher voltage levels in distribution or transmission grid and are often both visible and controllable by the system operator. For solar PV and wind turbines connected in lower voltage levels, this usually complicates getting real-time measurement data (less observability of changing output) and the possibility to control the output from system operators if needed. This can be taken into account considering two categories of PV/wind: distributed, which only modifies the net load shape (load minus wind/PV); and utility scale power plants, which the system operator can control for curtailment or reserve purposes. Smart inverter functions (such as fault ride through, active power frequency response, remote active power dispatch, and/or voltage/reactive power control) are increasingly requested for PV and wind systems in the distribution level. The dynamics of the controller can change when the regulations change, and also this should be included. Existing inverters can also be updated to include new capabilities, for example different response times. If no detailed track of PV/wind capabilities is available, the PV/wind capabilities can be included as a study variant.

Active power (for steady state studies and UCED, power flow analysis, etc.): Active power is representing all possible control functions, enabling the active power output to display specific behavior (ramping up and down, delta, etc.). This control represents the capability of wind and solar 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 and solar forecasting and on-line monitoring. ICT and communication signals introduce a delay and reliability issue that may be relevant to take into account in very fast response services.

Reactive power (for steady state and dynamic stability studies): Reactive power capability represents the control features enabling PV panels, wind turbines and wind/solar power plants to provide reactive power to assist in voltage control and 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.

Fault Ride Through, Active Power Frequency Response and Inertial Response need to be modelled in the stability studies and are described more in detail in Section 6. Second generation of generic models have been published for wind power plants by WECC (Ellis et al. 2011), while the IEC working group has recently published the first edition of an IEC standard (IEC 2015). Models for large PV systems have been developed from the previously developed WECC wind plant models as many commonalities exist between PV systems and wind plants comprised of 'type 4' wind turbines (i.e., full power converter wind turbines).

For offshore wind power plants connected via HVDC transmission, the modeling requirements depend heavily on the study scope. In many cases, it is sufficient to limit the modeling to the onshore HVDC inverter and use a simplified aggregated wind plant model. Such an approach is particularly valid when onshore voltage and reactive power issues are in focus, because the DC stage decouples reactive power flows in the offshore AC system from the onshore grid. However, when discussing active power control and system frequency support, the relation between the HVDC controller, the centralized plant controller, and the individual turbine controllers must be addressed (Zeni et al. 2014). Again, communication delays and response times are important when quantifying the response during the first few seconds after a disturbance has occurred. For fast transients in the millisecond range, the dynamics of the DC system are important, which will require detailed models to be simulated on shorter time steps (Asmine 2011).

2.2 Load Data

Hannele Holttinen, Emilio Gomez, Enrico Maria Carlini

Load data should be coincident to wind/PV data to capture any underlying correlations, and with the same time step (usually hourly, or 10–15 minutes). Load data has daily, weekly, and usually also seasonal patterns that can in principle be used to simulate time series data. Simulated data is in many cases easy to generate, however, if temperature dependence is strong this should be captured in simulated data, with temperature data coincident with wind and PV data.

Load data can be scaled up to future demand time series with simple demand growth assumption—however this is getting more challenging as electrification - like changes in electric vehicles and heat pumps- will change also the load profile. Adding roof-top PV will mean that only net load is seen in many cases, and native load growth is not being tracked in historical time series. An analysis of historical data combined with long term forecasting is needed.

It is essential for capacity value calculations to capture the correlations of wind and solar energy 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 to capture higher variability of high wind years. For power 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 modeling and for scheduling energy transfer in advance. In order to allocate reserves, uncertainties of the load forecast, together with other uncertainties of the power system, has to be considered. If historical 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). For temperature dependent loads, two parts need to be considered: one temperature dependent, another part non-temperature dependent. 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 information on the location of (future) load and wind/PV 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. Nor using an appropriate load dynamic model can impact the results for wind/PV integration impact (WWSIS 3). Load models are also improving as a result of multiple R&D activities (Milanovic et al. 2013; Arif et al. 2017).

2.3 Grid Data

Grid data is needed in detail for network models, and in some simplified manner for unit commitment and dispatch (UCED). For power capacity (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. The assumptions regarding the interconnections (NERC 2011) may be critical (Ibanez and Milligan 2012).

2.3.1 Transmission Grid and Interconnection Data

Enrico Maria Carlini, John Olav Tande, Til Kristian Vrana, Hannele Holttinen

Renewable sources are often distributed (dispersed) over large areas and far from demand centers. For future power systems, new long-distance transmission capability and transmission strategies may be required to deliver large amounts of power over long distances. Transmission planning is often one of the main goals for network simulations, but transmission scenarios are also important to take into account in other simulation models. A robust transmission expansion plan is important to take into account for longer term studies with high shares of wind and

solar. The details of the network modeled should also be commensurate with study objectives – more detail needed for more detailed studies.

UCED models are evolving to also include transmission, and DC power flows are available in several models, increasing the accuracy of the model. Traditionally, the simplest simulation methods have been used, assuming copperplate (i.e., perfect transmission) inside areas and modeling only the key transmission paths between areas or transmission zones such as Net Transfer Capacities (NTC) available from operational data. In regions that use locational marginal pricing, such as market areas in the United States, it is already common to develop a nodal transmission model that has more detail of the transmission network. It is challenging to take into account the flexibility option from neighboring areas through interconnectors, in cases where including all neighboring areas will make the simulation task too large. Assuming a completely flexible interconnection capacity at all times will probably overestimate the flexibility available, and 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, the representation of the network is by topology, line rating, and impedance. Operational methods such as dynamic line rating (DLR)—also called Real Time Thermal Rating (RTTR)—connected loads, and generation must also be adequately represented depending on the scope of study (i.e., steady state power flow or dynamic/transient).

High-voltage direct current (HVDC) lines can be represented in a similar way as AC lines, where line rating (mostly publicly available) and resistance (can be estimated from public data) are sufficient for power flow calculations. Additional electrical parameters (e.g., inductance) are needed for studying dynamics, which also can be estimated based on public data. HVDC converter stations and also other controlled devices like reactive compensation units, phase shifting transformers, etc., pose a significant challenge. These controlled devices are difficult to model correctly. The physical data like voltage and power ratings is often available, but information on their control structure and implementation is often not publicly available. However, the control system is highly relevant for dynamic studies. The control system modeling is therefore often limited to being only a best guess based on experience, so the possibility of incorrect modeling should always be kept in mind. The relevance of this problem is steadily increasing with the growing share of such devices in the power grid. The models that can be used, both for steady-state studies and for electromechanical dynamic studies with the associated controls, suitable for the majority of the technical performance AC/DC interaction issues associated with an HVDC link embedded in an AC network are introduced in CIGRE 536 (2013). A summary on the main dynamic modeling schemes is provided in CIGRE (2007).

2.3.2 Distribution Grid Data

Steffen Meinecke, Markus Kraiczy, Barry Mather

Distribution grid data is needed for dedicated distribution grid studies. Additionally, a representation of the distribution grid for larger transmission system models is needed for detailed studies when a large share of generation is distribution-connected. When representing the distribution grid for transmission networks, it is important to preserve the necessary details, but still have the models feasible for simulations.

The data handling usually depends on available data information and analysis methods, which depend on the scope of the study. Common approaches of data handling can be divided to the following scopes:

I. Detailed analysis of new algorithms, methods or other solutions for distribution grids

Reasons to choose this approach: scarce input grid data forces the use of open and available benchmark grid data[4] (e.g. Strunz et al. 2009; Christie 1999). The study goal is to test new algorithms and the analysis focuses on easy-to-compare results and transparency.

Exemplary scope and best practices: test new local or central operation management strategies for improved voltage control (e.g., Bonfiglio et al. 2014 using the CIGRE 2009 network), reactive power provision for transmission system operators (TSOs), congestion management, island system mode and network reconfiguration

II. Detailed analysis for single or few distribution grid sections (local or regional scale)

Scope: analysis of a single or few (predetermined) grids in detail. Available data information: usually detailed (generation, consumption and grid configuration).

Exemplary scope and best practices: detailed PV/wind interconnection studies, power quality analysis (e.g., FRT), local voltage stability analysis and detailed assessment of operational methods (Wang et al. 2017).

III. Comprehensive distribution grid studies on regional or system wide scale

Methods and best practices:

a) Analysis of representative grids in detail: a determination of representative grids is often performed by clustering/taxonomy of distribution grids/feeders (Schneider et al. 2008; Broderick 2014; and Von Meier et al. 2015).
b) Analysis of bulk system: automated (simplified) analysis techniques, possibly with assumptions of simplified grid data, e.g., topology (Büchner et al. 2014; Höflich et al. 2012; and Jäkel 2015).

Available data information: Often, no detailed information is available for all grid sections as well as generation, consumption and grid configurations. This significant lack of data leads to a need for further assumptions and/or data derivation.

Exemplary scope: Analysis of grid reinforcement costs due to wind/PV integration (hosting capacity), distribution grid bulk system behavior (grid stability) and distribution efficiency analysis.

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[4] Benchmark data sets for state-of-the-art solutions in grid analysis, grid planning and grid operation are currently developed in the SimBench-Project (further information: https://www.simbench.de/en/welcome).

2.4 Power Plant Data—For other power plants than wind/PV

Hannele Holttinen, Jody Dillon, Emilio Gomez, Enrico Maria Carlini, Peter Børre Eriksen

The behavior 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 (also see Section 3.1 on portfolio set-up).

Wind/PV 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/PV power as well as the generation capacity 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 shares of wind/PV power where the adequacy during also the seasons when the outages are traditionally planned needs to be studied. Conventional generation uncertainty can be represented by the capacity outage table computed using the unit's outage replacement rate (see Section 4). The distribution of the power station outages should be adapted to the future power plant mix.

- For UCED modeling:
  - Plant technical characteristics and constraints: ramp rates, minimum up and down times and start/stop costs, minimum stable levels and heat rate curves. Details of capability with respect to various operational reserves and frequency regulation.
  - Fuel prices: this is a critical input to production cost simulations, particularly the relative prices of different technologies. It is often desirable to consider multiple fuel price scenarios.
  - Details such as forced and scheduled outage rates allow simulation of forced and maintenance outages. The cost impacts of increased cycling of plants are sometimes included in more detailed studies.
  - For CHP (Combined Heat and Power) units, additional, plant-specific data is needed for both extraction units and back pressure units. Data for connected heat storage tanks and heat demand of connected district heating systems are also important.
  - For hydro power plants with reservoirs or pumping possibilities, the storage capacity and constraints of the river systems need to be taken into account. The variability of inflows over different time horizons (day/week/year) is important to capture. Hydro power plants without reservoirs (run-of river) can be modeled in the same way as wind, i.e., based on statistical time series of water inflows.
- For dynamic calculations, the dynamic behavior and capabilities are modelled. 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, if available, from disturbances, such as switching of power lines, loss of generation or

loads and balanced faults (see also Section 6). The control capabilities of power plants are evolving, as are the grid codes.[5]

2.5 Demand-Side Management and Storage

Juha Kiviluoma, Hannele Holttinen, Enrico Maria Carlini, Ana Estanqueiro

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/UCED simulations and should also be used in capacity value estimation. They can enable optimal use of networks and impact the transmission and distribution network adequacy. The storage technologies can also have an impact on the stability and long-term dynamics of power systems. The modeling 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. Requirements to provide demand response services to relevant grid operators in Europe are defined by the available Demand Connection Network Code (DC NC)[6]. One of the Demand Side Response capabilities specified in the Network Code is the System Frequency Control, e.g., the decrease or increase of the temperature set point proportionally to the frequency deviation in order to counteract the frequency behavior.

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 storage has 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.

DR is not a single technology. There are multiple, very different possible sources of DR, which have different benefits, costs and constraints. From the modeling perspective, the challenge is

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[5] Requirements like so-called Frequency Sensitive Mode and Synthetic Inertia facility, as well as strategies to cope with under/over-frequency are mentioned in the available Requirements for Generators Network Code (NC RfG): Commission Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators, entered into force on 17 May 2016.

[6] Commission Regulation (EU) 2016/1388 establishing a network code on demand connection, entered into force on 7 September 2016. To ensure that they provide the minimum degree of harmonization required to achieve secure of electricity supply, in the near future the European Commission will establish a specific Network Code in the area of demand response, including aggregation, energy storage, and demand curtailment rules.

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/PV power, it is probably best to concentrate on DR sources that could offer relatively large amounts of MW and/or MWh flexibility. 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 sources of controllable MWs, and it can be cost-efficient to equip some of them with (partial) response capabilities for the purpose of automatic and/or manually activated frequency 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/heat 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. A review of demand response from the viewpoint of solar and wind power integration was made by Nolan et al. (2014).

Most forms of electricity storage are rather expensive for balancing the energy between low and high wind/PV 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 are decreasing and have been evaluated in Schoenung (2011), Divya and Østergaard (2009), and O'Malley et al (2017) for batteries as well as Deane et al. (2010) for pumped hydro power.

2.6 Checklist of Recommendations for Input Data

Recommendations regarding the input data are summarized in Table 3.

Table 3. Recommendations for input data needed for the integration study components (for more detail of wind/PV generation data see Table 2)

	Capacity Value/ Power (resource) Adequacy	Unit Commitment and Economic Dispatch (UCED)	Power Flow	Dynamics
Wind/PV	Hourly generation time series for dispersed wind/PV energy covering the area. Especially for wind, more than 10 years recommended	5-minute to hourly generation time series of at least 1 year for dispersed wind/PV power covering the area	Wind/PV capacity at nodes, high and low generation and load snapshots, active and reactive power capabilities	Wind/PV capacity at nodes, high and low generation and load snapshots, dynamic models, operational strategies
Wind/PV Short-term Forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	May be needed in future	Not needed
Load	Hourly time series coincident with wind/PV data, at least 10 years recommended	5-minute to hourly time series coincident with wind/PV, of at least 1 year	Load at nodes, snapshots relevant for wind/PV 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	May be needed in future	Not needed
Network	Interconnection capacity, if relevant	Transmission line capacity between neighboring areas and/or circuit passive parameters	Network configuration, circuit passive and active parameters	Network configuration, circuit parameters, control structures
Other Power Plants	Rated capacities and forced outage rates	Min, max on-line capacity, start-up time/cost, ramp rates, min up/down times. efficiency curve, fuel prices	Active and reactive power capabilities, system dispatch	Dynamic models of power plants

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3 Portfolio Development and System Management

Lennart Söder, Hannele Holttinen, Jody Dillon, Michael Milligan, Juha Kiviluoma

This chapter describes the blue Set-up boxes (Figure 11 red circle) of the wind/PV 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.
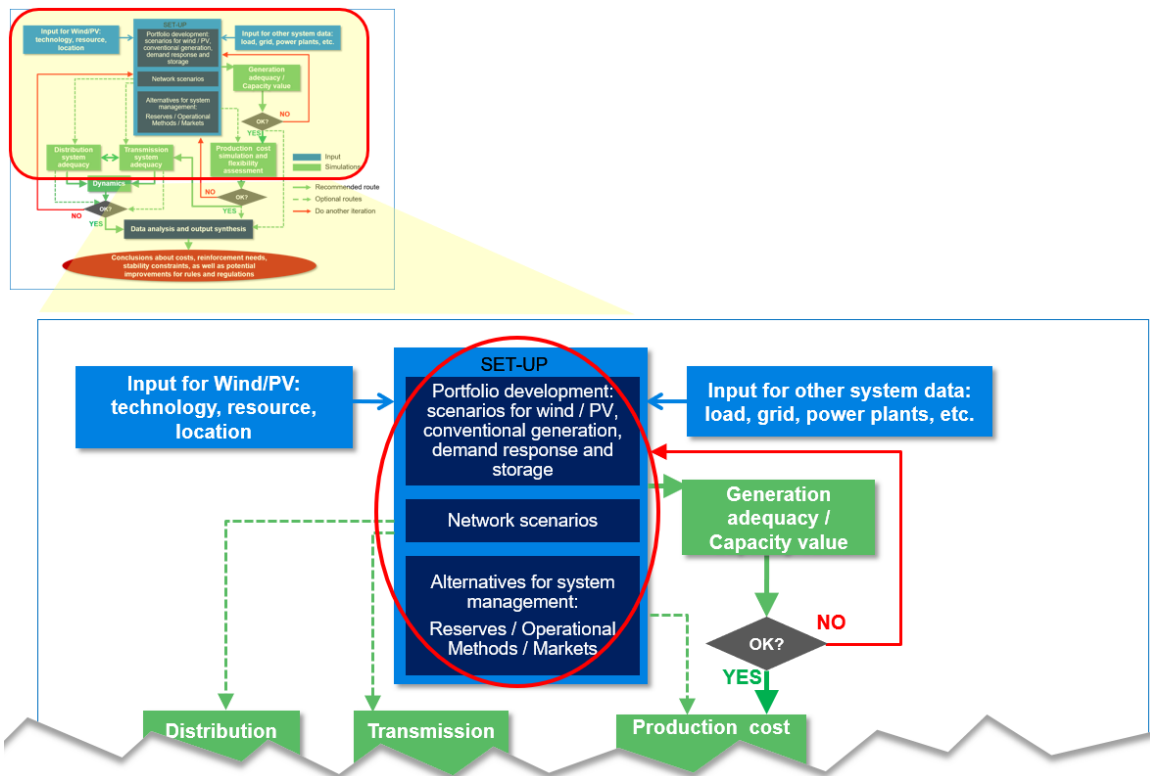
Figure 11. Wind/PV integration study components: portfolio development, transmission scenarios, and changes in system management

The purpose of a wind/PV integration study and the main setup chosen will have crucial impacts on the results. Different goals mean different approaches and can also impact the methods. Often the motivating questions relate to the technical impacts of wind/PV power, like reliable system operation, reserve requirements, balancing and generation efficiency and flexibility needs, capacity value, efficient use of existing network or requirements for new network investments, and system stability. Sometimes the goal is to find out how much wind/PV is technically possible, or how much is possible without changes in system. Some studies are so-called "green-field studies" in order to optimize a far-future situation, while other ones assume that a large share of current investments are still available.

In addition to estimating integration impacts, the value of wind and solar may be a question, as well as reductions in value with high shares of wind/PV. The challenges in extracting the value of wind/PV in simulations are similar to challenges in extracting integration cost impacts from system simulation results. Choosing the base case to compare with will be important for results drawn from the comparison of two simulation runs.

The main decision regarding portfolio development is what kind of system is studied—now or in the future. In most cases, the higher shares of wind/PV power will be relevant for a future (not current) system and then adding wind/PV will replace older generation capacity. Capacity expansion model runs may be used in portfolio development; these model runs can produce optimized generation portfolio scenarios for higher shares of wind and solar, and take into account the risk of generation plants getting decommissioned if used for too few hours.

Transmission capacity, generation mix, and operational practices including market design and reserves are important inputs to wind/PV integration study calculations. The setup chosen for the study may give rise to limitations as to how much wind/PV power can cost-effectively be integrated. Important iterations will feedback from later phases of the integration study simulations because changing generation and transmission, or operational practices, may be required to cost-effectively integrate larger amounts of wind/PV power. The assumptions regarding the available flexibility, technically, and operationally will have significant impacts on the study results and implications for balancing needs. Neighboring areas can provide flexibility as well, and deciding how to take that into account can be very important. Including also other sectors than electricity (like heat, gas, and transport sectors) may provide flexibility and enable integration.

Usually, a target of the share of energy being supplied by renewable resources is used. It is important to consider that wind and solar systems have different capacity factors (average generation as a percentage of nominal generation capacity). Capacity factors for PV normally vary between 10-30%, depending mainly on latitude and cloudiness. Typical capacity factors for new wind power plants are between 25-50%, depending on the wind resource and turbine characteristics. For example, a 20% annual wind energy share means that wind energy could potentially be generated at any hour of any day, subject to resource characteristics. Conversely, a 20% energy share for solar will only occur during daylight hours; thus, an energy-equivalent share of solar will have concentrated impacts during approximately half of the day compared to wind energy.

Another important factor is the correlation of generation with peak load situations. In systems with a summer peak, caused by a high use of air-condition, the capacity value of PV is significantly higher than in a system with a winter peak and a low amount of sunshine in the winter.

The "low" and "high" share considered in this report depends on the system: 5% may be a lot in some systems, whereas 10% could be considered low in others. It also depends on the share of solar energy, as we note that the operational impact of the same share of wind and PV will differ significantly.

3.1 Generation Portfolio and Transmission Scenarios

Lennart Söder, Jody Dillon, 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 far in the future is the studied system assumed to exist - if it is rather close in time then most of the existing infrastructure and other power plants will remain whereas further in the future new more flexible technologies can be assumed to replace old ones.

- How to take neighboring areas into account in simulations.
- How wind/PV power is added—replacing some existing (older) generation; adding to an otherwise unchanged system; adding with an alternative generation like a block load of same energy content; or through a portfolio development (optimization) process.
- Assumptions regarding available flexibility, both technical and institutional/regulatory.

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

- What will the composition of the generator fleet be in the future years? If large amounts of wind/PV 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. The mix of inflexible base load units relative to more flexible resources will make a large difference in the ease or difficulty in integrating wind/PV 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/PV 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/PV integration study component "power adequacy/capacity value" has an iteration loop back to the generation portfolio in Figure 2. For longer term studies, capacity expansion models may be used to optimize the future generation mix for higher share wind/PV power systems. The market operation will also impact whether that optimized capacity will be built. For example, energy-only markets may not provide sufficient revenue for future high shares of wind/PV.

For most regions in the world, less wind power capacity is needed than PV capacity to meet target energy shares. This, together with seasonal variations in the solar resources in many places, could also affect portfolio development.

Transmission networks help efficiently integrate wind and solar power. Increasing network capacity provides a means to get the electricity to where it is consumed, and also enables the sharing of flexibility between neighboring areas. Network scenarios are an important input for simulations, and they are also one output of the study: how much new transmission/distribution is needed to accommodate the foreseen wind/PV power. This usually means iterations from the power flow simulations back to the network scenarios. Meeting ambitious targets that have been set for wind/PV energy will often require upgrades to the existing network infrastructure and the construction of new lines. However, if congestion of the existing transmission or distribution network is not severe, curtailing wind/PV power or maximizing the use of existing lines may be more cost effective, and faster, than building new lines. Economic network planning with wind and solar need to capture the whole picture—8,760 hours of power flow—with cost and benefit analyses for the whole power system. The new transmission assets will not just transmit wind/PV generation; they will also enhance the security of supply and

facilitate the connection of other power generation and enable electricity markets and balancing over larger geographic areas. Therefore, assigning costs and benefits for wind and solar, using a causal framework is not likely to be accurate.

The main recommendations based on these issues are as follows:

1. When studying small amounts of wind/PV power or short-term studies, wind/PV power can be studied by adding wind/PV to an existing or foreseen system.
2. For larger shares and longer-term studies, changes in the assumed remaining system become increasingly necessary and beneficial: expedient generation portfolio and network infrastructure development, taking into account potential sources of flexibility (also demand response), and technical capabilities of power plants (dynamic stability responses).

What is considered a small amount will depend on the system: 5% may be a lot in some systems, whereas 10% could be considered low in others. It also depends on the share of solar energy, as the operational impact of the same share of wind and PV will differ significantly. With large wind/PV share (>50-70% in yearly energy), changes are so important that the system to study becomes completely different from the one we know (e.g., integration of power electronic interfaces with RES, reduction of synchronous machines and inertia). This means that conclusions from "simple" studies regarding viability of such a system have to be taken with great care, and additional and more complete studies will be needed.

3.2 Operational Practices and Markets

Michael Milligan, Hannele Holttinen, Juha Kiviluoma

Power system operational methods and electricity 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/PV power at increasing shares. 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/PV 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/PV energy.

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 grid support services (ancillary services such as various reserve types for frequency control) 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.

Practice with scheduling, dispatch and ancillary services can have a significant impact on the efficient integration of wind/PV 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). Closer to real time operation—continuously updating forecasts and utilizing online-measurements of wind and solar—will reduce the amount of deviations that need to be corrected at balancing markets (or balancing time scale where no markets exist). This also impacts the size of allocated reserves. One example of this is the Western Wind and Solar Integration Study, 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 distribution of new wind and solar generation in that study, the existing operating practice may not be effective in integrating 35% wind and solar energy.

- In some cases, it may be economic to curtail wind/PV 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. Integration studies can directly simulate this by using a downward-dispatch price offer for wind/PV, allowing the production simulation model to economically curtail if, and when, it is economic.

- It is important to take into account the system support services (ancillary services) that wind/PV plants can provide (frequency and voltage control) at larger shares of wind/PV. This will help to reduce curtailments (van Hulle et al. 2014; Kiviluoma et al. 2012). More recent market designs allow for wind and solar, and smaller assets to bid their available flexibility to ancillary services markets (such as the European balancing code[7]).

Operational methods may change with the addition of transmission and/or more flexible generation (e.g., new transmission interconnection to neighboring 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/PV 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/PV power.

Where market structures are inhibiting access to flexibility, they may need to be changed. Examples include reducing dispatch times and/or lockdown periods so that the latest information about wind/PV can be incorporated into the dispatch. Most existing centralized markets include an energy market, and some include balancing/regulation markets. It may be necessary to take neighboring areas into simulations in order to capture the possibilities to share flexibility in day-ahead and balancing time scales. For example, in the North European Nordic market system operators from four countries cooperate and use the cheapest regulating bids to

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[7] Commission Regulation (EU) 2017/2195 of 23 November 2017 established a guideline on electricity balancing

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.

Market assumptions can also be a barrier, creating artificial costs such as increased imbalance costs at higher shares of wind/PV, with non-realistic network constraints. An integration study can consider new market design and regulations and determine whether they are sufficient and how they could be improved to enable higher shares of wind and solar.

Key operational and market issues include:

- What is the institutional setting of the future time period to be analyzed? Will markets evolve to include products that enhance flexibility, or will fast dispatch/balancing be sufficient? Should capacity markets be included? 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/PV 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 modeling approach to account for interchange that correctly captures actual (or future) practice?
- Will reliability-based balancing criteria be the same in the future? This would have a significant impact on wind/PV 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/PV or short-term studies.
2. For higher shares and longer-term studies, additional scenarios or operating practices should be studied. Market structures/design to enable operational flexibility, should be assessed.

What is small amount will depend on the system: 5% may be a lot in some systems, whereas 10% could be considered low in others. It also depends on the share of solar energy, as we note that the operational impact of the same share of wind and PV will differ significantly. With large wind/PV share (>50-70% in yearly energy), changes are so important that the system to study becomes completely different from the one we know (like integration of power electronic interfaces with RES, reduction of synchronous machines). This means that conclusions from "simple" studies regarding viability of such a system have to be taken with great care, and additional and more complete studies will be needed.

3.3   Reserve Allocation—Estimating Changes Due to Wind/PV Power

Michael Milligan and Hannele Holttinen

System operators carry reserves to balance load and generation, and to respond to outages. The impact that wind/PV energy has on procuring operating reserves is an on-going area of research, taking the uncertainty of wind/PV power into account while aiming for both reserve adequacy and economic provision (for wind: Holttinen et al. 2012; for PV: NREL 2013).

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 analyzes for increased reserve requirements due to wind/PV 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/PV 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. Impact on contingency reserve that is used to cover large failures is often ignored because it is not generally affected by wind/PV power and most systems do not plan contingency reserves to help manage large wind/PV power ramp events (Holttinen et al. 2012; Gil et al. 2011). To determine the 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 will 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).

A correct modeling is crucial for a realistic estimation of the impact on reserve capacity when the amount of wind/PV power increases. The computation of reserve requirements requires estimates of the uncertainty and variability of demand, wind/PV generation, and other generation sources. Some reserves may be allocated for real time variability only. For wind and solar power, the forecast horizon is a crucial assumption, because the uncertainty at shorter time scales will reduce more significantly than demand. Demand forecasts are often based on standard load profiles with fewer updates.

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/PV 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.

It should also be noted that an increased level of reserve due to wind/PV power may be supplied by already present conventional generators that are used to supply energy in the non-wind/PV case, and therefore supply less energy and more reserve in the wind/PV case (for example, in a situation with high wind/PV power production, other power plants are running on a comparatively low level and could then increase their output to compensate for fast wind/PV 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.

3.3.1 Recommended Methods

A common approach is to compare the uncertainty and variability before and after the addition of wind/PV generation. Adding wind/PV 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/PV generation on operating reserves (Menemenlis 2012; Milligan et al. 2010; Ela et al. 2010; Ela et al. 2011; Holttinen et al. 2012; for solar NREL 2013).

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 realized, power is imported from neighboring balancing areas. For example, one might choose to cover 95% of the variations in net load (load minus wind/PV power) of the balancing area, based on existing operating practice of balancing area reliability metrics in use. 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/PV 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 exceedance 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/PV 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 (Meyruey 2016). 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). Similarly, PV uncertainty is lower on clear days compared to cloudy days. High solar power variability is often observed during times with fast moving clouds (Lave 2012).

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/PV 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/PV power is usually lost, as this means operating with reduced output levels. At high wind/PV 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 neighboring 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. For solar PV, larger balancing areas are beneficial to connect large-share areas with those that have less PV installed (Bloom 2016). However, the higher correlation of PV generation between regions during clear sky conditions means that such benefits are more quickly diminished compared to wind, as increasing amounts of PV are installed or if neighboring regions have similar amounts of PV shares.

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/solar power, or short-term studies, integration can be studied by adding wind/solar to an existing, or foreseen system without major inaccuracies
  - For larger wind/solar shares and long-term studies, changes to the remaining system become increasingly beneficial and necessary: expedient generation portfolio and network infrastructure development, taking into account potential sources of flexibility (also demand response) and technical capabilities of power plants (dynamic stability responses).
- Operational methods:
  - Existing operational practice can be used as a starting point when studying small amounts of wind and solar power or short-term studies.
  - For higher wind and solar shares, additional scenarios or operating practices should be studied. Assess market structures/design to enable operational flexibility.
- Reserve requirements/allocation method:
  - Input data: Coincident wind/PV and load time series (at least hourly) and wind/PV/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/PV 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/PV and load (and generation), keeping the same risk level before and after adding wind/PV. 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 shares, use dynamic, not static allocation methods for committing reserves.

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4 Generation Capacity Adequacy and Capacity Value

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This section describes the first simulation box of the wind/PV integration study components flow chart (Figure 12 red circle).
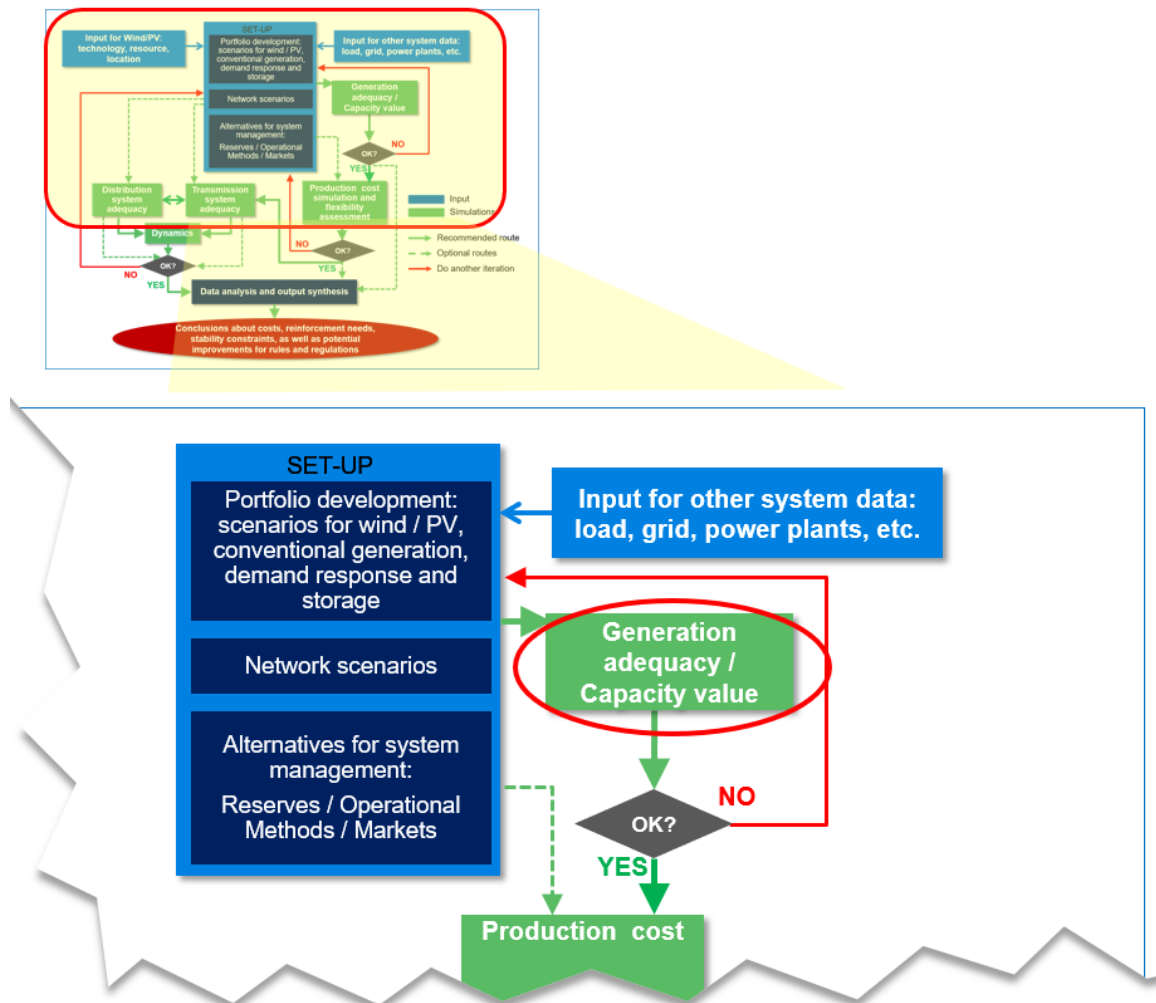
Figure 12. Wind/PV integration study components: estimating capacity value of wind/PV power

This section considers established methods for capacity value evaluation of specific generation assets. The same methods also assess the generation capacity adequacy of the whole system. If the reliability[8] (resource adequacy) target is not met by the power plant scenario, iteration is

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[8] 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

applied to change the portfolio to include more generation capacity or fewer loads through load reduction or demand response. The capacity value calculation should recognize transmission possibilities to bordering areas.

Capacity value estimates the impact of a specific (generation) asset to the generation capacity adequacy of the whole power system. New wind power and/or PV add generation capacity to the power system and as such their direct impact to the capacity adequacy can only be positive or at worst negligible. The exact value is important for system long-term planning, ensuring generation capacity adequacy (also called resource adequacy) of the future system. It can also be used when estimating the need for capacity to be auctioned in capacity markets.

Adding wind/PV capacity will also influence the profitability of existing and planned power system assets. There is no reasonable method to discern the long-term capacity impacts of any one new asset—it is a system property where the causal chains are not likely separable. A practical approach is to leave the capacity adequacy to the markets and more importantly to the system operators and regulators who are responsible for it. Notwithstanding, it is worthwhile to evaluate the capacity value of wind power and PV—it is an actual value that can be highlighted as one result from an integration study.

The capacity value of wind and solar PV is heavily influenced by the availability of the resource at the time of peak system load. In summer day peaking systems with large air-conditioning loads, solar PV has an advantage while wind energy has a disadvantage, as it is common to have lower winds in the summer. The opposite is often true for winter peaking systems where the peak occurs in the early morning, late afternoon, or evening. However, at higher variable renewable shares, the effective timing of peaks is expected to change due to the impact on the net load, requiring a more robust calculation method for capacity values.

Using storage to improve capacity value of wind/PV in future systems is possible; we already see domestic roof-top PV being complemented with storage units in some places. From a power system perspective, the approach so far has been to calculate wind and PV capacity value separately, and then let storage be one option (from the system point of view) to cope with potential problems in capacity adequacy. When storage system operation is determined from a single PV/wind power plant point of view, while providing potential value in eased interconnection, higher potential revenue, etc., the overall system ultimately operates in a non-optimal way from a capacity value perspective. Due to complementarities between wind and PV, a system achieves operational benefits and greater production with a combination of both resources compared to a single technology.

4.1 Methodologies and Models

Capacity value studies in various power systems have been undertaken utilizing 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

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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.

of the wind and solar regime and the characteristics of the demand profile (e.g., whether peak demand occurs in winter or summer). Some of the lower values reported in wind integration studies 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 and solar capacity value decreases with increasing generation capacities. This is due to the correlation between the output of new and existing wind and solar power plants. New plants tend to produce during those hours when there is already generation and not so much during those hours where the generation is more limited.

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).

The correlation between wind/PV generation and peak load situations strongly influence the results. Hence, many years of coincident load and wind/PV data are needed. The resulting answer cannot be relied upon if sufficient data of the required quality is not available (Hasche et al. 2010; Milligan et al. 2017). In addition to multi-decadal data sets for wind/PV and load, the ELCC method requires a complete inventory of conventional generation units' capacity and forced outage rates.

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 existing or targeted reliability level in the power system can greatly impact the capacity value of both conventional power and wind/PV 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 capacity value calculation should recognize possible imports through transmission lines from bordering areas, even when considering a specific area of the power system. For large interconnected systems with higher shares of wind/solar generation, multi-area power system reliability would be needed (Tomasson et al. 2017a and c; Terrier 2017). Monte Carlo methods using unit commitment and dispatch may be more suitable for capacity adequacy assessment, as they can consider operational issues and have an endogenous approach to transmission constraints (ENTSO-E 2016). In principle, they could also be used for assessing the capacity value of a specific generation asset; however, if specific methods are not considered, then crude Monte Carlo approaches can take considerably more computational resources and are consequently not practical for the iterative approach needed to establish the capacity value of an asset. How to make a suitable Monte Carlo set-up is discussed in Section 4.1.2.

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 utilizes the datasets that capture the full relationship between load and wind/PV, it provides the

best assessment of 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.

4.1.1 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). The same method is equally valid for assessing the capacity value of solar power generation. The method can be applied to both separately, but in some cases, it could be informative to apply the method for aggregated wind/PV, including storages installed.

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/PV generation.
3. Wind/PV power cannot be adequately modeled by its capacity and FOR because availability is more a matter of resource availability than the plant availability. Time series for the wind/PV power output is treated as negative load and combined with the load time series, resulting in a load time series net of wind/PV 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/PV generation.

4.1.2 Approximation Methods

Monte Carlo methods are approximations in the way that only a certain number of samples from a distribution can be used. This means that for large systems, with years of data and different possible combinations of wind levels, load levels, PV levels, thermal unit availability, and transmission availability results in a huge amount of possible combinations. However, there are, so-called, important sampling methods which can be used in order to concentrate the evaluation on the problematic situations, i.e., combinations that could result in outages. These methods are presented in (Tomasson et al. 2017a and c) and have also been applied in one large real multi-area system (Terrier 2017) and also for estimation of multi-area capacity credit (Tomasson et al. 2017b). With the right set-up of the method, the accuracy can be high and computation time realistically low.

An alternative risk calculation to the preferred method is the multi-state approach, which utilizes a probabilistic representation of the wind power plant (d'Annunzio and Santoso 2008). This may be extendable to PV with suitable adjustments. 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/PV 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/PV 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). This could be justified for solar, as the clear seasonal and diurnal patterns in the generation have a specific correlation with local peak loads. Although capacity factor approximations may be useful as quick screening methods for wind power (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/PV and hydro levels and outages is somewhat similar than the recommended method regarding COPT. However, it is difficult to preserve the auto- and cross correlations between wind, PV and load when generating Monte Carlo scenarios using a model. A more straightforward approach is to only use real data that preserves the underlying correlations correctly. However, as with COPT, this requires very long coincident data sets in order to capture extreme events.

It is essential to consider the utilization time of generation units when comparing the capacity value of wind/PV power with, e.g., a base loaded unit. To generate 100 GWh/year about 40 MW of wind power (utilization time 2,500h), 50 MW of PV (utilization time 2,000h) or 15 MW of coal power (utilization time 6,700h) is required. Note: if PV is distribution-connected a considerable decrease in aggregated capacity factor should be expected as such systems often do not include tracking systems, optimized tilt and azimuth, and may experience regular shading. 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. Consequently, it is more appropriate to compare the capacity credits in MW for the same yearly energy production instead of the percentage values.

4.2 Checklist: Capacity Value

Checklist of Key Issues: Capacity Value

- Gather chronological synchronized wind/PV and load data that captures the correlation with wind/PV and load data. This is of paramount importance, and the robustness of the calculations is highly dependent on the volume of data collected—10 to 30 years is recommended. 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/PV generation. Wind/PV is added as negative load, and load is increased until the same LOLE is reached as would be the case without wind/PV power.
- Insufficient data can necessitate the usage of approximation methods, which can provide useful insight. However, the limitations of such should be recognized. The same methods can be applied for wind and solar separately, or in aggregate

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5 Production Cost Simulations and Flexibility Assessment

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This section describes in detail the Production Cost Simulation and Flexibility Assessment box (Figure 13 red circle) in the wind/PV integration study components flow chart. First, important issues in production cost simulation (UCED modeling) with wind/PV power are described. UCED studies are frequently the main tool for evaluating power system flexibility. However, flexibility assessment as a separate tool is emerging as an important step in integration studies for higher shares of wind/PV power. This is discussed subsequently.
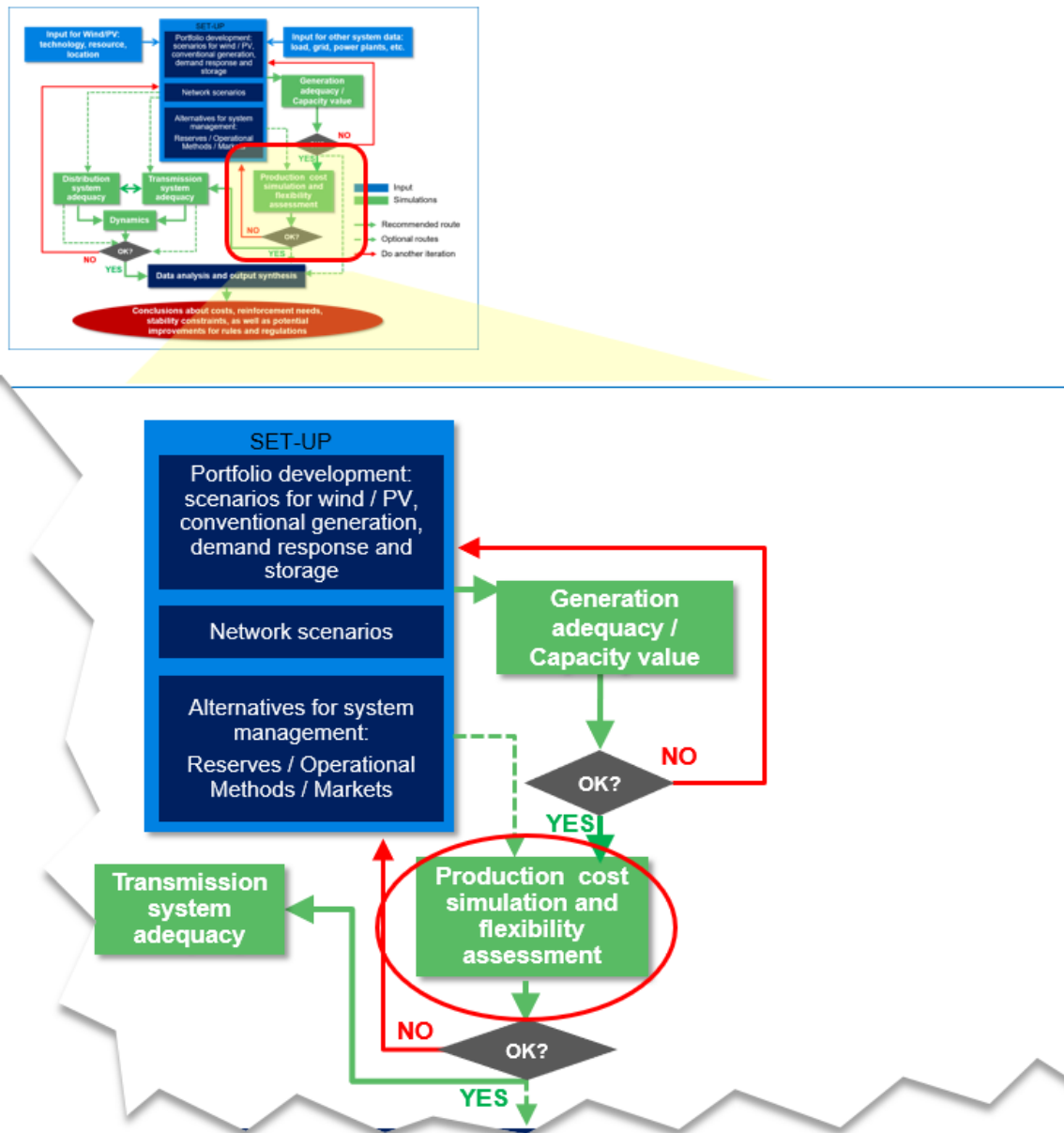
Figure 13. Wind/PV integration study components: production cost simulations and flexibility assessment

For longer term studies with high shares of wind and solar, the remaining system may be optimized using a capacity expansion optimization, often as a separate tool. The generation

adequacy may be checked with loss of load calculations involving a longer input data set, where also the capacity value of wind or solar can be estimated.

Flexibility can be described as the ability of the power system to respond to change. For wind and solar integration, flexibility is required to manage the resulting variability and uncertainty to ensure that demand balance, security and adequacy constraints are met. Longer term studies should also take into account possible adaptations to technologies to increase flexibility like more transmission lines and controlling power flows in transmission (FACTS, etc.) as well as increasing flexibility in conventional power plants, in demand and by adding storage. Better wind/PV power forecasts and possibility to Wind/PV power curtailment, when there are no other more cost-effective ways for flexibility can also be used. Electrification of heating, cooling, and transport with flexibility measures may also bring new flexibility.

Flexibility resources will help integrate wind and solar in the power system. They may also be seen as a means to increase the system value of wind and solar (IEA 2016).

5.1 Production Cost Simulation

Production cost simulation is the main study vehicle used to assess the impacts of wind/PV power integration on system balancing, flexibility, operating costs, and emissions. It involves optimizing 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/PV power. Production cost simulation is comprised of Unit commitment and economic dispatch (UCED), to simulate optimal short-term energy balance in the power system.

The analysis is usually carried out at a resolution of hours and for a minimum duration of a year. However, driven by the need to capture issues over longer time frames (such as capacity adequacy for example) or shorter time frames (such as frequency regulation and automatic generation control (Ela and O'Malley 2012), the analysis can be extended in duration and/or time resolution to capture different issues of concern. Usually many model runs are carried out in order to represent a range of possible future scenarios of, for example, fuel prices, conventional generation portfolios and economic factors.

In a fully developed model, the constraints in the optimization ensure the physical feasibility of the short-term operational plans and reliability under uncertainty. For example, the committed units can be required to manage frequency control with reserve allocation, as well as meet the ramp requirements over multiple 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/PV 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.

5.1.1 Simulating Wind and PV Production

The variability of wind/PV 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. For PV power generation time series, using satellite data, general weather forecasts (clear, partly cloudy, etc.), meteorological models, or a combination of these has proved more robust. There is usually at least some correlation between wind/PV and load and therefore the time series should be co-incident. Capturing the impacts of wind/PV power requires simulations at sufficiently high enough

temporal resolution. Hourly time scale is often considered detailed enough, but 10–15-minute time steps better captures ramping constraints experienced by conventional power plants. High time resolution issues can often be captured either explicitly (by running the simulations at sub-hourly resolution) or implicitly (by including constraints which capture the issue indirectly, such as ramping constraints). Characteristic variability of wind power and loads from several different power systems has been documented in Holttinen et al. (2011), and Section 2.1.

5.1.2 Simulating Uncertainty

Wind/PV power also introduces additional uncertainty, which needs to be considered. At higher wind/PV shares, the day-ahead uncertainty from wind/PV 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) and solar in Tuohy et al (2015). For load forecasting, the accuracy does not improve that much with decreasing time horizon. How the uncertainty in the wind/PV plant output forecast is handled with respect to the load forecast uncertainty is important.

The literature documents numerous methodologies for handling uncertainty. Stochastic optimization with rolling planning (Tuohy et al. 2009) has been used to explicitly represent the uncertainty as a function of forecast look ahead. Here, stochastic scenarios of load, wind, and PV are used in place of deterministic production time series. This can be considered a high-fidelity approach to capturing uncertainty impacts on power system, but such studies have onerous data requirements. The need to produce stochastic scenarios that sufficiently represent the actual uncertainty can add significantly to the cost and complexity of a study. Longer run times also mean that fewer macro level scenarios can be considered.

Recently, robust optimization has emerged as a methodology to capture uncertainty impacts in UCED simulation. Statistical uncertainty is translated into a deterministic "margin" or constraint that can be explicitly included in the UCED model without significantly increasing the run time. This approach effectively trades model complexity with stochastic fidelity; it often leads to a more pessimistic view of the impact of uncertainty on results, as the robustness constraints are often driven by the worst-case uncertainty scenario.

While it is important to consider the uncertainty impacts of wind and PV, it is also important to look at conventional generation uncertainties—particularly when system reliability is a concern and where generation outages and renewable forecast errors interact. Various statistical models exist to simulate forced outages and maintenance outages. For example, a forced outage rate and mean repair time is often used to represent unit forced outages as a semi-Markov process, which can be simulated to produce a unit forced outage schedule. Alternatively, thermal unit outages can be modeled using a Poisson distribution (Doherty and O'Malley 2005). In deterministic models, forced outages should be expected, and will only impact available capacity over the period of the outage. However, within a stochastic optimization model, this can be included as a source of uncertainty. Maintenance outages are usually simulated using a reliability assessment model.

5.1.3 Locational Issues

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 neighboring countries or areas. However, solar PV generation is generally coincident on a system-wide scale except for systems which cover relatively large distances east to west. It is also the trend in electricity markets to include several countries and

subsystems. To better capture these spatial impacts, simulation of all relevant neighboring areas is at least required or, indeed, simulation of the entire market area. Available interconnections and flexibility from neighboring areas form an important assumption which can heavily influence results (see Section 2

Input Data). Thus, it is important to capture at least the transmission capacity between regions and simulating the entire market area is best.

The scope of UCED simulations can be expanded to include an explicit representation of transmission. This is referred to as Security Constrained Unit Commitment (SCUC). This involves explicitly including the DC power flow equations in the model. Explicit inclusion of transmission constraints can be particularly important in the context of PV and wind interactions, which may limit production at a local level or have operational benefits. However, due to the increased data and computational requirements, explicit representation of transmission is not always included in UCED models, particularly when the system size is large or stochastic unit commitment is used.

A typical approach is to include grid congestion adjustments in UC models for a limited number to transmission paths, which have been identified as likely congestion points. Using the power transmission distribution factor (PTDF) and line outage distribution factor (LODF) approach for SCUC can be an effective way of accomplishing this, as constraints are only added to the model for each monitored and contingent line. This is an effective way to limit the computational impact while still capturing the important constraints.

An alternative approach is the use of total transfer capacities (TTCs), which are commonly used by TSOs to manage power flows between regions. Here, larger areas can be divided into multiple sub-areas, with set transmission limits between the areas (known as TTCs). These TTCs are usually lower than thermal capacities of lines between the regions; consideration is given to transmission constraints within each area and these limit the flows between areas.

5.1.4 Conventional Plant Modeling

Data for thermal plants should be detailed enough to capture variable O&M costs, operational costs (including heat rate curves, start-up costs and emission costs), constraints (including run-up rates, ramp rates, and minimum stable levels and minimum up/down times) and system (ancillary) service capabilities including, for example, operating reserves and frequency control.

In addition to simple ramp up and ramp down limits, which apply between subsequent time steps in a UC model, it is important to consider whether there is enough ramping capacity online to meet net demand changes over longer periods of time. This is particularly a concern in systems with large shares of wind and/or PV, and it may require additional explicit constraints to ensure the ramping adequacy of the system (see also Section 5.2). Co-optimization of energy, ancillary services, and ramping is already emerging as system operation practice in some regions (for example MISO in USA).

Wear and tear costs of ramps can also be included but at a computational expense (Troy et al. 2012).

Where appropriate, it may be necessary to include more detailed data on flexibility limitations, particularly in relation to balancing and ancillary service provisions (for example, minimum and maximum activation hours and lead times).

Flexibility can also be increased for example by retrofitting thermal power plants to enable more ramping and lower on-line generation levels.

5.1.5 Hydro Power Considerations

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 modeling 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.

To ensure that interactions with wind and PV are captured fully, time-dependent hydro input data should be co-incident with wind/PV/load data. UCED in systems with mixed thermal and hydro power plants with reservoirs poses a special challenge due to the need for optimizing the storage content over the year while UCED for thermal plants is usually a weekly problem. Besides the concept of "water value" is normally introduced, as cost of water is zero.

Hydro power flexibility can also be increased by adding capacity in reservoir hydro, or pumped storage.

5.1.6 Optimization Methodology

Two main optimization methodologies have been used to formulate and solve unit commitment models. Mixed integer linear programming (MILP) has the capability to handle integer variables such as those associated with the start up or shutdown of a generating unit. The impact of these integer effects is particularly significant at higher shares of renewables (Shortt et al. 2013). For example, with high instantaneous shares of wind and/or PV, the minimum stable level of online generators becomes hugely relevant in order for the simulated generator schedule to be physically realizable.

However, for large systems with many individual units, MIP models can have prohibitively long run times. For larger, interconnected areas, linear programming (LP) is often is used where on-off decisions are replaced by continuous variables meaning that integer inflexibilities such as minimum stable levels and minimum up/down times cannot be represented well. LP models can be useful for high level approximations and rough estimates over longer periods of time, and for large systems with relatively small amounts of wind and/or PV. However, LP models are not suitable for capturing the inflexibilities and operational detail of systems with large amounts of wind power that may, for example, drive curtailment of variable renewables.

Hybrid approaches exist within commercial tools that offer a trade-off between run time and integer. One such approach is rounded relaxation where continuous variables are used to represent integer decisions which are subsequently rounded to zero or one depending on their final value. Also, various decomposition approaches can be used and are often available in commercial tools.

5.1.7 Storage and Demand Response

Demand response and energy storage can be valuable sources of flexibility in systems with large shares of wind and/or PV and careful consideration should be given to their inclusion in unit commitment models. Demand response may take a number of different forms depending on the nature and flexibility of the resource.

Some demands can be disconnected for periods of time, usually at times of peak demand. This type of demand response is usually referred to as demand shaving (or load/peak shaving).

Other forms of demand response require a certain amount of energy consumption but are flexible regarding when the energy is consumed. This type of demand response is commonly referred to as demand shifting (or load shifting) and is similar to the flexibility afforded by storage. With demand shifting resources, there are normally additional timing constraints regarding the period within which the energy demand must be satisfied.

Electricity storage resources may have storage capacities that require optimization over periods longer than a typical daily optimization and thought should be given regarding how this is accomplished. Common approaches include attributing a shadow price to energy remaining in the store at the end of the optimization period, or performing a simpler optimization (often an LP model) over a longer period, typically a year, to produce daily storage targets.

5.1.8 Recommendations for Production Cost Estimations

1. Co-incident time series of wind/PV and load (at least a year, preferably several) 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/PV power and representative for real wind/PV power variations. In systems with significant amounts of hydropower, it is essential to consider different hydrological scenarios (e.g., wet/dry years).

2. With higher wind and solar shares, it is important to model the impact of short and long-term uncertainty on dispatch decisions in UCED, for example using a stochastic optimization and rolling planning method (Tuohy et al. 2009). The general diurnal pattern of solar PV is quite predictable, but weather effects like cloud cover can result in some uncertainty, particularly in temperate climates.

3. Increased operating reserve targets should be estimated using wind, solar and load forecast uncertainty. However, in calculating reserve requirements as a function of wind/PV uncertainty, care should be taken to avoid double-count the impact of uncertainty, particularly if stochastic optimization is used. With higher wind/solar shares, use of dynamic reserves, faster markets and increased market resolution is recommended. Assumptions about the operating rules and regulations in a future study can also include for example sharing of balancing resources across balancing areas.

4. 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 thermal plants, such as minimum generation levels, ramp rates, minimum up/down times, start times, load times. For hydropower plants, the degree of freedom to control power production and exploit filling/withdrawal of reservoirs also needs to take into account 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 or if wind/PV shares are relatively low and the system is large.

5. To accurately model the limitations of interconnections with neighboring regions, the neighboring system should be explicitly modelled, including also the wind/PV power installed there (such as ENTSO-E TYNDP 2016). Alternative approaches include assuming fixed flows obtained from other studies or based on assumed market prices in neighboring regions. These approaches will err on the pessimistic side and this should be mentioned clearly in the study conclusions.

6. To capture the limitations from the transmission network, congestion and N-1 security can be included directly within UCED (the system should always operate in a state where any single failure (N-1) could happen without compromising). To reduce the computational

burden for large systems or where stochastic optimization 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. Also, transmission systems limitations can be modelled in other dedicated tools and the resulting limitations included as constraints within the UCED model.

7. Depending on the study horizon and levels of wind/PV share, the possibilities from new sources of flexibility should be analyzed, if applicable (heating, cooling, electric vehicles, storages, demand response, dynamic line rating).

8. Study results and conclusions are particularly sensitive to the non-wind/PV case used as a basis for comparison and assumptions regarding the types of generation that wind/PV power will displace, especially if estimating integration costs. Using a scenario with equivalent wind/PV energy but with a perfectly flat power profile may result in impacts not entirely related to wind/PV energy (Milligan et al. 2010). The use of generation planning models to ensure consistent scenarios should be considered.

5.1.9 Markets

With increasing levels of wind/PV energy, it is important to capture more detail and the current constrained optimization paradigm has evolved accordingly. In addition to being used to study the impacts of increased levels of renewables in power systems, the main optimization methodologies behind production cost simulations are also those used to run and schedule markets and set pricing. Thus, these recommendations for production cost simulations with large amounts of wind and PV power also apply to the mechanics of energy markets, which may need to evolve also (Kiviluoma et al. 2012; Dragoon and Milligan 2003).

Market mechanisms may need to take into account the risk of losing too much unprofitable generation capacity, which could jeopardize generation capacity adequacy.

Possible adaptations to the optimization paradigm with high levels of wind and/or PV by changing the rules include increasing commitment/spot market frequency, adding intra-day markets and regulation markets, using stochastic unit commitment with dynamic reserve, higher resolution UCED like 15 minutes instead of hourly, complex bids (e.g., block bids, ramp limits), coupled optimization of energy and transmission and larger balancing areas.

Table 4 details how the rules may need to be changed at some point when the share of wind/PV 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 analyzed.

Table 4. Evolutions for short-term energy balance with increasing shares of wind/solar energy (Kiviluoma et al. 2012)

	Explanation	Scheduling Frequency	
		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/PV 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	Optimization of UC decisions over several scenarios for possible outcomes of wind/PV 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	

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/PV 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/PV 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 it has comparatively high capital costs for new installations. Reducing costs and increasing wind/PV shares have increased the importance of storage as an enabling technology that should be taken into account in studies.

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 incentivize 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 minimize 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/PV share.

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 shares of wind/PV power. For the future, there will be a need for cross-sector models for investigating the additional flexibility to be achieved by integrated planning and operation of power, heat, mobility and gas (power to gas).

For studying larger shares of wind/PV 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/PV 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/PV energy studied.

5.3 Checklist: Production Cost Simulations and Flexibility Assessment

Checklist of Key Issues: Production Cost Simulations and Flexibility Assessment

- Co-incident input data for wind, PV and load with at least hourly resolution and one year is required. 10-15 min time steps and multiple years would be preferable. Capturing the spatial smoothing of wind/PV power production time series for the geographic diversity assumed is important. For hydro dominated systems, the hydrological changes (wet/dry year) need to be captured, and co-incident data is needed for run of the river hydro. Wind/PV forecasting best practices should be used for the uncertainty of wind/PV power production, assumed for the year of study, with possibilities to update forecasts closer to delivery hour using rolling planning.
- 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, minimum up/down times, minimum stable levels, start-up and shutdown limitations. Cycling impacts and the associated costs may also be important as well as hydrological constraints in case of hydropower. The operational practices that may enable or limit flexibility to be used should also be taken into account.
- Take into account the possibilities of flexibility that exist in neighboring regions. To accurately model the limitations of interconnections, the neighboring system should be explicitly modelled, including also the wind/PV power installed there. Alternative approaches include assuming fixed flows obtained from other studies or based on assumed market prices in neighboring regions. These approaches will err on the pessimistic side and should be mentioned clearly in the study conclusions.
- To capture the limitations from the transmission network, congestion and N-1 security can be included directly within UCED. To reduce the computational burden for large systems or where stochastic optimization is used, net transfer capacity, or iterative methods can be used. Also, transmission systems limitations can be modeled in other dedicated tools, and the resulting limitations should be included as constraints within the UCED model. 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/PV case used as a basis for comparison and assumptions regarding the types of generation that wind/PV power will displace, especially if estimating integration costs. Just adding wind/PV power, or using a scenario with equivalent wind/PV energy, but with a perfectly flat profile, may result in impacts not entirely related to wind/PV 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/PV energy studied. We recommend that for higher wind/PV shares, a scope that acknowledges and/or includes new potential sources of flexibility be made.

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6   Network Simulations: Power Flow and Dynamics

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This section covers those simulation parts relating to the network simulations and dynamics (Figure 14 red ellipse) in the wind/PV integration study components flow chart.
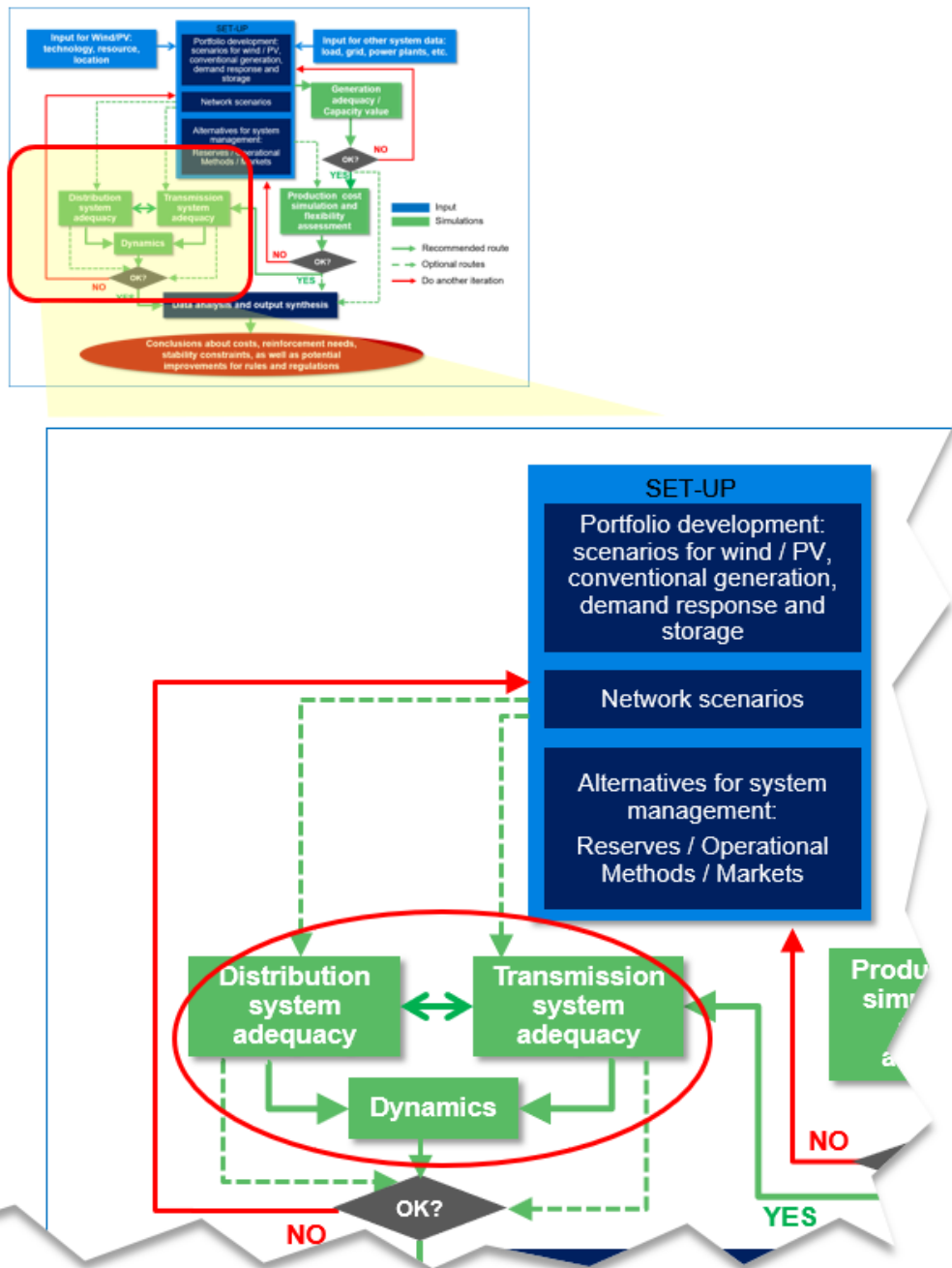

Figure 14. Wind/PV integration study components: transmission scenarios, power flow and dynamics

Once production cost simulations have indicated that a given wind/solar integration scenario is potentially feasible, more detailed analyses should be performed, to assess if the combination of plant portfolio and (transmission and distribution) grid are sufficient to cope with both

temporary disturbances and significant failures. It is noted that the incorporation of generation 'must-run' and locational constraints within production cost simulations may have implicitly addressed some known network and stability issues. More detailed analyses can include steady-state power flow; N-1 contingency analyses; contingency assessment and stability analyses; power quality and harmonic analyses. The need to assess any impacts on power system stability will be important especially with higher (instantaneous) shares of wind/PV power.

The chosen deployment of wind generation (including different wind turbine technologies and wind distributions) and solar generation (including different solar PV and concentrated solar technologies and residential uptake of installations) can also be evaluated against existing network code requirements and considering different mitigation or participation options.

Power flow and dynamic simulations can also provide inputs to the production cost simulation—reflected in the transmission scenarios for portfolio development, perhaps as part of an iterative process. If the power flow and/or dynamic simulations reveal deficiencies, then a wide range of options should be considered, depending on the likely frequency of occurrence and severity of the consequences, ranging from a revised economic dispatch/unit commitment for the system, to modified control and/or supervisory schemes, and grid reinforcement and/or enhancing network functionality, e.g., introducing load-tap-changing or phase-shifting transformers. An iteration loop can be formed to the portfolio setup relating to transmission scenarios. Similar simulations can be conducted as part of transmission planning, whereby objectives include relieving existing congestions, arbitrage between markets, and maintaining (or improving) security of supply (transmission adequacy). A host of system conditions must be analyzed as part of a transmission expansion plan.

In order to assess the impacts of wind/PV power on the transmission system, various network contingency situations are typically studied, with the results compared against the criteria for acceptable power system operation and safety, as established by the network code (system operator). Typically, this involves steady-state power flow analyses; system reliability analyses through probabilistic methods; optimal load-flow for selected scenarios and, often, dynamic system stability analyses.

The complexity and focus of an integration study may change substantially between successive phases of the assessment, as seen in Western USA - Phase 1 (WWSIS 2010), Phase 2 (Lew et al. 2013), Phase 3 (Miller et al. 2014) and also for Ireland - Phase 1 (AIGS 2008), Phase 2 (EirGrid and SONI 2010) and Phase 3 (EirGrid 2015). With low VG shares it is probably sufficient to study those steady-state and dynamic issues which are historically associated with a particular system. It will be important to understand whether an increasing VG share tends to exacerbate or improve known operational issues. At higher VG shares it may be prudent to study a much broader spectrum of contingencies and analyses, firstly through a high-level scanning approach and then adopting a more in-depth approach as interesting and challenging issues are revealed.

6.1 Study Case Definition

Steady-state and dynamic studies have traditionally (not for wind/PV integration) involved snapshot analyses of particular cases, where those periods of greatest system stress are well known, e.g., annual peak load. However, depending on the correlation of diurnal/seasonal load patterns with wind/PV 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/PV generation as independent variables, which may limit the number of additional cases

considered, e.g., low demand coupled with high wind/PV production, but the likelihood of occurrence of such scenarios may not be significant. Where possible, wind/PV and demand time series should be employed, in order to capture any underlying correlation. Multi-year analysis should perhaps be considered in order to capture less common but threatening scenarios.

As part of the system set-up, locational issues need to be recognized, whereby, for example, significant wind/PV generation is located in one region while high demand hubs are located elsewhere, leading to an assessment of the network's ability to transfer power from *source* to *sink*. Similarly, wind/PV generation should not simply substitute for conventional generation on a 1:1 basis, as in actual system operation some units may be dispatched down while others are switched off. Recognizing the changes in the unit commitment and economic dispatch as wind/solar are added to the system is of key importance and will have later implications for interpreting stability analysis results (Miller et al. 2014).

Consequently, a number of credible power flow base cases (perhaps linked to market model simulations) that represent high shares of wind and/or solar generation should be created. As above, these cases need to reflect:

- High/low load
- High/low solar power output
- High/low wind power output
- High/low import or export (to neighboring systems)
- Full/empty storage

Such an approach might result in $2^5 = 32$ cases, but this number could be reduced by focusing on those cases that would represent some of the more challenging conditions for the system, perhaps 4 to 8 scenarios. In addition, uncommon but extreme low load days, e.g., bank holidays, and/or high load days could also be considered. An example set of scenarios might include: Reference scenario; High local generation/low load; Low local generation/high load. Winter and summer variants could also be specified, leading perhaps to a total of six scenarios. Rather than identifying here a definitive set of scenarios to be considered, the peculiarities of a particular system need to be recognized, e.g., underlying correlation between wind/PV production and high/low demand periods and the resulting probability of occurrence of extreme scenarios, the locational distribution of wind and solar generation sites relative to each other and to demand hubs.

From a (steady-state) power flow perspective, high-low cases might be best for assessing network loading, reverse power flows, etc. However, from a stability perspective, those cases of interest could be entirely different, and may be more associated with low headroom available from conventional power plant, displacement of generation incorporating stabilizing controls (e.g., PSS for oscillation damping, displacement of inertia "assets"), voltage and reactive power capability during (network) maintenance periods, locational concentration of distributed generation leading to reverse power flows. Recognizing the capabilities of wind and PV technologies added to the system should form part of any investigation.

Stability studies have traditionally (not for wind/PV integration) involved snapshot analyses of particular cases, where periods of greatest system stress are well-known (e.g., annual peak load). Depending on the correlation of diurnal/seasonal load patterns with wind/PV generation output, periods of system stress may occur over a much broader range of the year. A simplistic approach can consider system demand and wind/PV generation as independent variables,

which may limit the number of additional cases considered (e.g., low demand coupled with high wind/PV production). However, the likelihood of occurrence of such scenarios may not be significant. Where possible, wind/PV and demand time series should be employed to capture any underlying correlation. Multi-year analysis could be considered to capture less common but threatening scenarios. Locational issues may also arise. for example, if all wind/PV generation is in one location and a high demand occurs somewhere else, whether your network can transfer the power from A to B should be questioned. It is important to set up the case carefully; usually wind/PV do not substitute other generation 1:1, because in actual system operation some conventional generation may be dispatched down and some may be de-committed. Understanding the new commitment and dispatch patterns with the addition of wind and solar is important and should be used to set up the stability cases (Miller 2014).

6.2 Steady-State Analysis

6.2.1 Power Flow Calculation

Power flow analyses are performed to check possible bottlenecks (congestion) in the transmission network and to assess the system's capacity to maintain the voltage profile. When bottlenecks are set by thermal stability considerations, then such analysis, also considering re-dispatch, is sufficient, otherwise dynamic studies are needed. The effect of wind/PV energy production on the voltage profile differs according to the type of renewable energy units (e.g., PV generators, asynchronous generators, doubly fed asynchronous generators, synchronous generators connected via converters). Therefore, depending on the assumed technology and the network connection rules, an appropriate level of reactive power absorption/production and controllability should be simulated to determine the need for reactive compensation and to assess the conformity of the voltage profiles.

Steady-state studies may also choose to consider the emerging opportunities and benefits of implementing dynamic line rating of the transmission network. It should be emphasized that when taking into consideration the dynamic (thermal) behavior of the lines, in most circumstances, the wind resource that leads to the maximum loading of the lines, also introduces the maximum cooling effect, depending on the relative proximity of the wind farm(s) and the particular overhead lines, thus alleviating the load factor of the lines. It should be noted, of course, that the introduction of dynamic line rating, as with many other initiatives, implies the upgrading of energy management systems, the integration of external measurements, the availability of real-time contingency analysis, etc. Power flow controllers and utilization of SVC/STATCOMs and other FACTS devices may also be considered.

6.2.2 Modeling Distribution-connected Wind/PV

An inherent difficulty in suitably representing the distribution network is that when modeling a contingency, the area over which a transmission-level fault causes a significant voltage sag needs to be determined and the aggregated response of the many distribution-connected wind/PV plants is a function of the considerable voltage diversity present in the distribution system. This voltage diversity is present due to the relatively high impedance of the distribution circuit, compared to transmission lines, and the distributed and somewhat variable loading of distribution circuits. The most common approach to account for the voltage stability impacts of high levels of distribution-connected wind/PV is to aggregate the distribution-connected wind/PV using a simple model which attempts to approximate the impact of voltage diversity (WECC REMTF 2014), and then use the resulting voltage sensitive model in a traditional transmission-level voltage stability analysis. Industry wide consensus regarding the best practices for the tuning of aggregate distribution-connected wind/PV model parameters has not

yet been formed, but analytical methods involving both transmission- and distribution-level modeling have been proposed (Boemer et al. 2017; Mather and Ding 2016).

6.2.3 (Steady-State) Contingency Analysis

Contingency analysis can be performed by conducting power flow calculations deterministically for all possible N-1 situations or stochastically by, for example, Monte-Carlo simulation. Initially, a first screening to identify potential transmission bottlenecks caused by additional wind/PV generation can be carried out, although final decisions on optimal network reinforcements should be taken after a more comprehensive probabilistic analysis (see Section 6.4).

6.2.4 Short Circuit Level Calculation

The short-circuit power ratio, calculated at each bus, highlights the response (traditionally known as the "stiffness" or "strength") of the power system regarding power quality supply (namely voltage quality). Short-circuit levels across the network are characterized both before and after the addition of wind/PV power. For high wind/PV shares, some synchronous generation will not be dispatched, which may lead to a reduction in the minimum short-circuit level and a reduced short circuit ratio. (In contrast, the presence of wind/PV generation in remote locations might actually improve the short-circuit level in these locations.) This, in turn, may affect the power quality, magnitude of voltage step changes after shunt switching, and the operation of line commutated HVDC converters and PV/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 capability of the circuit breakers. However, the local power quality may be affected, and its impact should be assessed.

6.2.5 Harmonic Issues and Modeling

Traditionally, harmonic distortion has not been a major cause of concern at transmission voltage levels, since the majority of the non-linear loads were connected at lower distribution voltage levels, and the network is mostly comprised of overhead line circuits. However, the proliferation of renewable source generation connections utilizing power electronic converters introduces new challenges regarding the management of harmonic distortion levels. Moreover, these renewable connections are frequently implemented using underground cable circuits at high voltage (HV) and extra high voltage (EHV) transmission levels. The transmission network is usually weak at those remote locations and the incremental connection of generation utilizing power electronics can cause a further reduction in system strength by displacing conventional synchronous units in the generation merit order dispatch. The combination of new harmonic injections introduced by the power electronic converters and the resonance amplification effects introduced by the new HV/EHV cable connections can drive the harmonic distortion levels at the Point of Connection (PoC), and further into the transmission network, outside the Planning Levels.

Against this background, it is noted that detailed information and guidance on how best to model and analyze harmonic issues is at worst lacking and at best scattered across a range of documents which are often difficult to access. The CIGRE Joint Working Group C4/B4.38 (Network modeling for harmonic studies) is in the process of creating a technical brochure, due for publication in early 2018. In advance of the publication of the technical brochure some

general guidelines for the completion of harmonic studies can, however, be made (Val Escudero et al. 2017):

- When representing wind/PV (partial/full) power converters as a harmonic current source, the interaction between the converter and the power system impedance needs to be carefully represented, recognizing that the resonance frequencies can shift.
- For each scenario considered, two or three demand levels should be assessed in order to recognize seasonal variations in damping and shifts in harmonic resonance frequencies. The status of any reactive compensation devices should be defined for the different demand levels. Caution is advised, however, in unnecessarily de-committing generation plant in the surrounding test region to avoid overly pessimistic results, leading to over-investment in corrective measures.
- As part of assessing the impact of network contingencies, outages of transmission lines, transformers, generators, converter bridges, reactive compensation devices, etc. should be evaluated. The number of nearby outages considered as part of a contingency should balance the overall likelihood of occurrence against the cost of mitigation. The system operator should specify security criteria in typical situations for planning and operational conditions.
- While it is standard practice to combine harmonic sources (with unknown phase angles) using the summation law presented in IEC TR 61000-3-6, measured data suggests that the results can be misleading when combining wind farm emissions (Koo and Emin 2016). More generally, the summation law should be applied carefully when considering any modern harmonic source.

6.2.6 HVDC Grids

Til Kristian Vrana, Damian Flynn

The DC transmission infrastructure itself is relatively simple to represent, compared to the AC transmission infrastructure, due to the nature of direct current:

- Only two instead of three conductors
- No reactive power/current
- Constant values in steady state (unlike the 50 Hz fluctuation of all AC quantities)

The calculation is therefore comparatively straightforward: a true DC power flow, which yields precise results rather than approximations (when AC networks are analyzed using simplified DC power flow approaches).

For power flow calculations, when the DC transmission losses are neglected, it is often sufficient to omit HVDC transmission details, and to just represent the inflows and outflows of a given HVDC system. This will mean that the HVDC converter stations are modelled as simple AC power sources, supplying the exact set points (minus converter losses) for active and reactive power. When the HVDC system contains uncontrolled meshes, the power flow in the DC system has to be calculated a priori, to determine if the active power set points of the converter stations result in a viable flow on the DC lines. This DC power flow has to be also calculated when the DC transmission losses are to be considered.

For stability analysis, more complex issues arise for HVDC modeling. The presence of HVDC transmission infrastructure, especially future HVDC grids, can make the development of network simulations somewhat challenging (mainly where dynamic modeling and stability assessments are required). The details are outlined in Section 6.3.2.

6.3   Stability Analyses

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The need to assess the impacts of wind/PV generation on power system dynamics becomes increasingly important at higher shares: once the studied instantaneous share of wind and solar energy exceeds 30-50% on a synchronous system. Low instantaneous shares of wind and PV generation are unlikely to have a significant impact on system stability, beyond those issues normally seen for a particular system. The stability issues of concern for a particular system will depend on system size, wind/PV distribution relative to the load and other generation, along with the UC and network configuration. Operational challenges are likely to be first seen during the night (wind only) or seasonal low-demand periods when instantaneous wind and/or PV penetration may be high, even in cases when the annual energy contribution is still not very high.

Dynamic studies are required in order to ensure that the system is robust against a variety of system events and disturbances. Iterations should 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., ensuring a critical clearing time above predefined thresholds to warrant system stability.

For the execution of dynamic analyses, inputs from the transmission (and distribution) system structure (including previously selected reinforcements) and from the UCED are required. Stability studies will require much greater detail concerning the generating units than UCED simulations. UCED will provide steady-state snapshots of the power system for varying demand levels and wind/PV generation patterns. Such analyses should already recognize a range of dynamic issues, e.g., ramping capabilities of committed units, spinning reserve requirements, local network constraints.

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

- *Transient stability (i.e., angle stability)*: ability to maintain generator synchronism when subjected to a severe transient disturbance. Network behavior should be analyzed in the event of faults, determining the voltage and frequency oscillation ranges, and stability margins in the event of major contingencies.
- *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, system frequency variations and generator synchronism are not an issue.
- *Frequency stability*: ability to maintain the system frequency following a major imbalance between generation and load, e.g., tripping of the most heavily loaded lines or largest generator infeeds.
- *Voltage stability*: ability to maintain an acceptable voltage profile after being subjected to a disturbance.

Combinations of the above categories can also be envisaged, e.g., voltage dip induced frequency dips (McMullan et al. 2014; Rather and Flynn 2017). Additional interactions may result between the transmission and distribution networks, e.g., the loss of distributed generation due to transmission-level faults from protection activation and sympathy tripping (O'Sullivan et al. 2014). For the latter case, generators connected to the distribution system often have voltage trip and/or voltage ride-through settings which are effectively a compromise between bulk system stability and distribution system protection concerns. Additionally, older

generators may have been interconnected without considering bulk system impacts. These voltage-related operational settings lead to the possibility that transmission-level faults which suppress the voltage over a relatively wide-area could affect a large number of distribution-connected wind/PV plants, which in aggregate become a potentially significant contingency (Miller et al. 2014).

With appropriate dynamic data, studies can consider a wide range of issues:

- Determine if the grid is sufficiently robust to sustain both temporary disturbances and significant (dimensioning) contingencies, and capable of recovering satisfactorily from those events; and
- Evaluate the chosen deployment of wind/PV against existing grid code requirements, while considering different mitigation or participation options that the regulatory regime allows.
- Investigate the impact of different distributed generation locational distributions on stability issues, e.g., voltage stability assessment
- Assess the transmission limits when these are set by a combination of transient stability, small-signal stability and/or voltage stability concerns.
- Assess the impact of sub-synchronous interactions as part of small signal stability analysis, including sub-synchronous resonance, sub-synchronous torsional interactions and sub-synchronous control interactions (Flynn et al. 2017).

The objective of the above analyses is to determine the optimal measures to avoid the risk of wind/PV generation curtailment due to dynamic constraints. This can be made either through adopting "soft measures", e.g., appropriate controller settings, introducing flexibility-based ancillary services, coordinated protection schemes, or through "hard measures", e.g., additional network reinforcements, constructing/retro-fitting both wind/solar and flexible generation plant. Iterative feedback may be required to the generation portfolio and transmission scenarios, and production cost modeling stages.

While Section 6.1 outlined high-level considerations when selecting base case scenarios, of particular interest include periods of time when there is a high share of non-synchronous generation online, when large exports of wind/PV power occur across an area, and when there is low online headroom available from conventional generation. Specific concerns to assess with higher shares of wind/PV are as follows:

- 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, or those connected by HVDC links (Gautam et al. 2009), the reduction in online synchronous inertia. (The rotating masses of variable-speed wind turbines are decoupled from the electric grid, implying the lack of an intrinsic inertial capability. Similar principles apply for PV plant.) 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).
- Periods of wind/PV power export from one region to another may result in voltage angle differences across a synchronous area beyond typical levels and may threaten angular stability, both from a small-signal (oscillatory) and transient stability point of view (Eftekharnejad et al., 2013; Quintero et al.). 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 (reducing online inertia and synchronizing torque) and replaced with wind/PV at medium- or low-voltage levels, located behind a

relatively large impedance, even if the wind turbines, for example, are equipped with grid-code compliant reactive current boosting (Boemer et al. 2011b).

- A slow recovery of wind/PV generator outputs (while meeting grid code low voltage ride through requirements) following a nearby voltage dip may be sufficiently large to cause a significantly large demand-generation induced frequency dip, a so-called voltage dip induced frequency dip event (Rather and Flynn 2017).

The literature on dynamic issues is evolving. Issues in simulations have been encountered, such as how (dynamic) load modeling impacts results, reverse power flow cases and cascading outages. Also, alternative options to RES curtailment following stability concerns are being studied, such as the utilization of battery storage to avoid (delay) network upgrades and consideration of other network controls like FACTS/SVC devices and synchronous compensators or demand response.

6.3.1 Input Data/Power Plant Models

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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. The modeling complexity required will depend on the nature of the analysis, balanced against the size of the system and computational power available:

- For large scale system studies, given that access to manufacturer models is often limited, it is standard practice to utilize generic wind turbine dynamic models developed by the WECC and IEC (IEC 2015; Sørensen et al. 2011; Sørensen et al. 2013; Sørensen et al. 2014; WECC 2014; WECC 2015), and which are intended for short-term (10-30 s) analyses. These capture the minimum performance required by most grid codes for the four basic types of wind turbine. Models for large PV systems have been developed from the previously developed WECC wind plant models, as many commonalities exist between PV systems and wind plants comprised of full scale power converter connected ('type 4') wind turbines (Hansen 2006b; WECC 2014).
- Frequency stability studies require the inertia, droop and governor settings of all units in order to both simulate individual unit responses and the combined system response to major faults or contingencies, and to assess changes in frequency regulation capacity. Due to higher rates of change of frequency and lower frequency nadirs associated with lower inertia systems it may also be prudent to evaluate the adequacy of existing conventional generator models (Meegahapola and Flynn 2015). A reduced network representation may be sufficient (EDF R&D 2015; O'Sullivan et al. 2014).
- Small signal stability studies require automatic voltage regulator (AVR) including power system stabilizer (PSS) settings and governor controls for synchronous generation. Unit commitment may need to consider whether an appropriate arrangement of PSS-enabled generators has been dispatched.
- Transient stability analysis must consider the effect of protection devices for both network and converter-interfaced generating equipment. However, boiler/steam turbine models are not required.
- In addition to modeling the response of PV systems, the aggregate response of distribution-connected PV system also depends on the distribution systems to which they connect. Industry consensus on how best to determine aggregate distribution-connected PV model parameters has not yet been formed, but analytical methods involving both transmission- and distribution-level modeling have been proposed (Boemer et al. 2017;

Mather and Ding 2016). Development of adequate dynamic distribution models with distributed wind, PV, storage systems, etc. is increasingly required. Here, especially, the complexity and diversity associated with the distribution level can represent a major challenge.

- Increasingly, wind power plants are being located offshore, and connected via HVDC transmission to the existing onshore grid. Modeling only the onshore HVDC inverter is sufficient in most cases, in conjunction with a simplified aggregate wind plant representation. If power control and system frequency support are under consideration, then representation of the HVDC controls, individual turbine controls and the overall plant controller should be incorporated (Sakamuri et al. 2017).
- Finally, although (dynamic) load modeling has generally received limited attention, the increasing shares of wind and solar generation on the distribution network, and with power systems becoming 'lighter' due to the displacement of conventional generation (reduced inertia), implies that load characteristics will more strongly influence system performance. Existing load models should be re-evaluated, and the time varying nature of the load composition, and hence the load models themselves, should be considered (WECC 2012; CIGRE 2014).

The technical performance of both renewable and non-renewable generation to support high shares of wind/PV generation is clearly important. Particularly, at higher wind/PV shares, validated and comprehensive wind turbine/PV 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 may well not be aware of the specific equipment that will be installed, particularly the control schemes associated with 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.

Generic wind turbine/wind power plant models

The term generic, also commonly known as standard or simplified, refers to a model that is standard, public and not specific to any vendor (Honrubia-Escribano et al. 2016), so that it can be parameterized to reasonably emulate the dynamic behavior of a wide range of equipment while not directly representing any actual wind turbine control or wind farm. Working groups from the International Electrotechnical Commission (IEC) and the Western Electricity Coordinating Council (WECC) have been actively working during the last few years to define generic wind turbine and wind farm dynamic models (Asmine et al. 2011; Sørensen et al. 2011, 2012, 2013, 2014; Fortmann et al. 2014; Honrubia-Escribano et al. 2015, 2016a, 2016b). Models have been defined for the four main types of wind turbines, i.e., type 1 (a directly connected induction generator), type 2 (same as type 1, but with variable rotor resistance), type 3 (doubly fed asynchronous generator, currently most widely used), and type 4 (fully-sized power converter, increasingly being used). Each model includes a set of parameters which may vary from one wind turbine commercial design to another. Manufacturers covering the majority of the market (Enercon, Gamesa, GE, Senvion, Siemens, and Vestas) have contributed to the model specifications, with internal model validation ensuring that the WECC (Ackermann et

al. 2013) and IEC (Sørensen et al. 2012; Zhao et al. 2015) models are applicable to their specific wind turbines. A default parameter set may be used in studies where the specific wind turbines are not known, but the parameters are used to account for variations in the dynamic behavior of different wind turbines.

Recognizing that wind turbines can expect to be operated in different control modes depending on the requirements in a network code, the existing WECC and IEC models cover several different reactive power/voltage control modes during normal operation and during voltage dips. Fast frequency responses are not directly implemented in the models, since this type of response is at an early stage of development and therefore not considered sufficiently mature for standardization, but the power reference points can be used to connect the generic models to a specific user defined control model. So, for example, additional adjustments and extensions to the Type 4 IEC generic model have been considered elsewhere (Hansen 2014; Sakamuri et al. 2017) in order to reflect the dynamic features of wind turbines relevant for active power and grid frequency control capability studies. Since the generic models represent simplifications of very complex systems, validation against manufacturer models presents a key role to demonstrate the capabilities of these generic approaches (Honrubia-Escribano et al. 2017; Goksu et al. 2016).

The relation between individual turbine controllers and the centralized plant controller must also be addressed (Kristoffersen 2003; Hansen 2006b; Miller 2014). In particular, communication time delays can compromise the ability to perform fast responding services, such as fast frequency controls. Furthermore, the response time of wind turbine inverters limits their ability to support the grid during the first 10s to 100s of ms after a disturbance has occurred. A study variant may be to assess the advantages of enhanced wind turbine capabilities, coupled with coordinated set point controls across a network area.

The generic models are typically intended for transient stability simulations spanning 10–30 s, where wind speed is assumed to be invariant. At present, there are no standard models available to investigate wind power variability for longer-term stability studies, although the need for such models will depend on the particular phenomenon being studied and the size of the synchronous area under study. Analysis studies for test periods extending to several minutes and longer need to consider the impact of varying wind speeds.

It has been observed that the generic models, taking into account validation against real data, may be especially challenging due to the activation of the crowbar device. In fact, crowbar operation is associated with active and reactive power transients, whose response leads to larger errors during the fault period. The crowbar model included in IEC 61400-27-1 is a simplification of a complex dynamic system that provides a good approximation in terms of reactive power performance. On the other hand, the drive train of a wind turbine is far more complex, as it considers more masses as well as active damping controllers used to damp drive train oscillations. Therefore, variations of the drive train eigenfrequency may depend on many parameters and vary between turbines of the same type depending on local conditions and parameter settings. In some recent studies (Honrubia-Escribano et al. 2017), two issues have been highlighted related to full-load operation. Firstly, the aerodynamic model is based on the simplified assumption that wind speed remains constant during the simulation. However, under field operation, blade behavior is more complex and cannot be accurately depicted with such a simplified approach. Secondly, the pitch angle control model is based on two PI controllers: one associated with rotor speed and the other with generator power. However, pitch control strategies for commercial wind turbines are implemented slightly differently from this IEC approach.

Generic PV plant models

Models for large PV systems have been developed from the previously developed WECC wind plant models as many commonalities exist between PV systems and wind plants comprised of 'Type 4' wind turbines (i.e., full power converter wind turbines). The generic PV plant models are implemented in various software tools such as GE PSLF, PowerWorld Simulator, Siemens PTI PSS/E or DIgSILENT PowerFactory (Elliott 2015; Lammert 2016). WECC developed the PVD1 model (WECC REMF 2014) specifically for use in modeling both central and distributed PV, with the latter being modelled in conjunction with WECC's composite load model (WECC REMTF and LMTF 2015) which contains a simplified model of a distribution circuit and additional loads as would be seen on an actual distribution system. As for conventional and wind/PVpower plants, the modeling assumptions and specific settings of the dynamic model are important to consider. One such issue should be whether a centralized plant controller is adopted or if individual PV system components (i.e., inverters) are used to implement voltage/frequency sensitive control/protection functions. If a centralized plant controller is used a more pronounced response could be expected, whereas a distributed control approach could yield a partial response for borderline contingencies due to a diversity of voltages and/or sensed quantities within a large PV plant.

Additional modeling requirements and capabilities

Beyond modeling the standard control requirements for wind turbines and PV generation, e.g., maximum power point tracking, voltage and reactive power support, the available control modes and capabilities of such generation technologies can significantly impact the power system. It is, therefore, increasingly important that such capabilities are incorporated within the generation models in order to best understand their implications and provide fair comparison with alternative approaches.

Fault Ride Through (transient stability studies): Fault-ride-through (FRT) assessment considers the capability of power plants to remain connected when (severe) voltage drops occur in the network, as a consequence of (secured) network faults, and to continue stable operation during and after a network fault, while respecting minimum voltage levels and duration limits specified by the so-called FRT profiles (Figure 15). In order to support the network voltage and frequency stability, FRT requirements, in particular grid codes, normally include the provision for fast reactive current injection by the power plant as well as post-fault active power recovery capability. Typically, the FRT requirements are specified in the form of a voltage profile (EWEA 2012), which indicates the retained voltage level, U_{ret}, the voltage, U_{clear}, at fault-clearance time, t_{clear}, and the recovery voltage level after time t_{rec} (EWEA 2012). The rising sloped line in the FRT profile neither represents physical wind turbine behavior nor grid voltage-time behavior (which in practice is oscillatory), but instead encloses the envelope of minimum voltage levels to be considered (to remain connected or not) against time after initiation of the network fault.
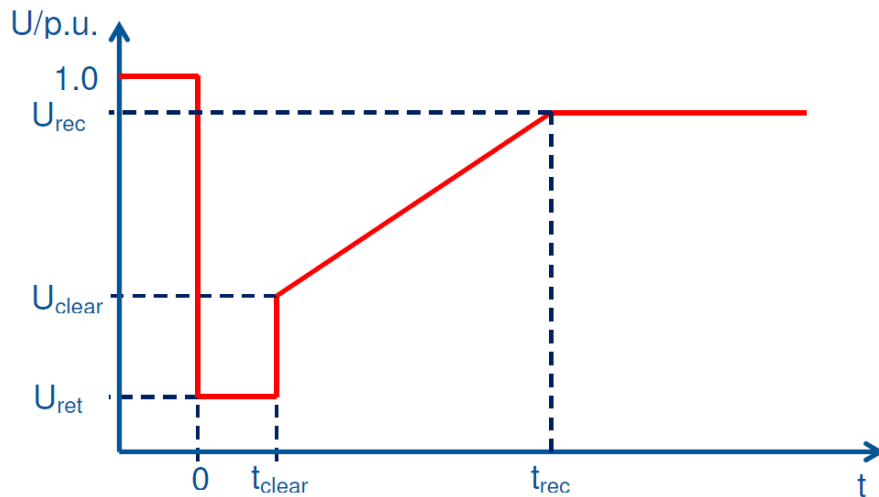
Figure 15. Generic FRT profile specified by the voltage at the connection point during and after a network fault (EWEA 2012)

Active Power Frequency Response (frequency stability studies): With an active power frequency response, wind turbines and PV plant provide an active power response in a direction which assists the recovery of the target system frequency, when the network frequency changes. The active power frequency response can be further categorized as: (a) continuous response (also called frequency sensitive mode[9]) or (b) a proactive response arising from a specified deviation (threshold) from the system frequency (also called limited frequency sensitive mode[10]). Technically, the active power frequency response capability enables the wind (or PV) plant, in principle, to participate in system reserves provision on different timescales. Given the control features installed in the wind/PV plant, the actual technical capability for providing a specified volume of upward response is dependent on the wind/solar conditions at the moment when the response should be provided, as well as on the level of de-rating applied by the wind/PV plant operator. The cost for providing this service will imply curtailed wind/PV power generation, so it is not normally provided continuously: instead, only during situations when a more cost-effective frequency response is not available, or if it is implemented in such a way that only a downward reserve is provided when required.

Fast Frequency Response (frequency stability studies): It is well known that synchronous generators, due to their rotating mass inertia, oppose changes in the system frequency through providing an inertial response. Since power electronic converters (and direct current (DC) lines) do not inherently exhibit such behavior, situations of high wind/PV share may lead to a diminished capability from the system to maintain frequency stability. Fast frequency response from wind/PV plant can be considered as a special case of an active power frequency response, but it is listed separately here because some grid codes make the distinction, and because sometimes it may involve specific wind turbine control features. PV plant can similarly provide

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[9] Commission Regulation (EU) 2016/631, establishing a network code on requirements for grid connection of generators, entered into force on 17 May 2016.

[10] Commission Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators, entered into force on 17 May 2016.

a fast frequency response, if operating in a curtailed state. The active power response provided is fast acting (much less than 1-2 s, subject to the details of the grid code, or other specifications) and can improve the frequency nadir (following a loss of generation) or frequency zenith (following a drop in demand, assuming that the implemented controls are bidirectional) particularly for larger systems (Brisebois and Aubut 2011; Rawn et al. 2010; Ruttledge et al. 2016; Sakamuri et al. 2017). It should be noted that the fast frequency response is not always available (dependent on weather conditions) and changes with wind turbine operating point (Ruttledge et al. 2012). Claims that such controls can improve the initial rate of change of frequency following a disturbance are often made but are difficult to substantiate.

Inclusion of protection systems: The disconnection of wind turbines (and also PV) due to faults can result in a large loss of active power infeed in some systems, making it important to accurately assess the extent of voltage depressions and the 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; CIGRE/CIRED 2018). However, the converter controls of PV plant and wind turbines complicate the analyses of small signal (oscillatory) and voltage stability. This argues for the continued development and support of accurate and field-tested PV and wind turbine models for use in stability analysis programs.

6.3.2 Considering HVDC Transmission Infrastructure

Unlike steady-state analysis, where representation of the DC transmission infrastructure may be sufficient, leading to a DC power flow, stability analysis for HVDC systems is somewhat more complex. The challenges are generally caused not by the DC network itself, but by the AC-DC HVDC converter stations that interface the HVDC transmission infrastructure with the AC grid. The behavior of these converters is determined mostly by their controllers and not by the physical properties of the devices (as would be the case for a synchronous machine). Different synchronous machines often have similar technical parameters, since they are constructed in a similar way: variations can stem from various technologies for the excitation system, different number of pole pairs, etc. However, HVDC converter station controllers can behave in a totally different manner (constant power control, constant voltage control, droop, etc.), and their control mode can easily be changed.

There are three converter types in use, which all show a different fault response.

- Voltage Source Converter - VSC (ABB HVDC Light generation 1-3)
- Modular Multi-level Converter - MMC
- Current Source Converter – CSC (Line Commutated Converter - LCC or alternatively Capacitor Commutated Converter - CCC), also known as classical HVDC converters

When simulating a network with HVDC transmission assets, introducing modeling assumptions is unavoidable. The control details (model and settings) of existing HVDC assets are usually not publicly available, making it challenging to implement their real behavior. Most studies, however, consider future scenarios, where future HVDC transmission assets would be considered, and their technology details and control mechanisms cannot easily be foreseen. Consequently, simulation conclusions, such as the system is stable, should always be treated with caution, and variations should be applied to the input assumptions (Vrana et al. 2016). Stability might depend on many factors (e.g., the control mode of the HVDC stations).

For offshore plant, with fast transients in the millisecond range, the dynamics of the DC system are important, which will require detailed models to be simulated with shorter time steps (Asmine 2011). When considering dynamic analysis, HVDC converter stations usually behave

in a highly non-linear manner for transient stability simulations. While for small-signal assessment, linearization can be effective, the large-signal response can be hard to predict with simplified models. Essential control features, such as IGBT overcurrent protection, can lead to a non-linear non-time-invariant fault response, which is hard to express through a simple single number such as the short-circuit-level. Software packages that focus on the power system (electromechanical) dynamics of interest can accurately simulate wind power plants connected through a voltage source converter (VSC)-HVDC (van der Meer 2010). Adopting a combined simulation strategy, i.e., stability simulation for AC grid dynamics, and electromagnetic transient simulations for DC grid dynamics, can provide an acceptable simulation speed and accuracy.

The number of HVDC transmission assets is steadily increasing in several parts of the world, especially Northern Europe, and also China. This leads to the observation that the above challenges are growing in importance over time. An example study considering a large number of HVDC assets can be seen in Vrana et al. (2016).

6.4 Transmission Network Reinforcement

Problems encountered in power flow or dynamic analyses can normally be resolved by reinforcing the transmission grid. The volume of network reinforcements required is a common outcome from grid integration studies. The constraints associated with the underlying transmission network are also an important input to production cost simulations. For the case of distributed PV (and wind), it is more likely that the distribution system will be the subject of reinforcement (see Section 6.5.2).

Given that wind/PV power often presents net load situations that are different from more traditional load scenarios, probabilistic analyses is a recommended future option when determining the most favorable transmission grid reinforcements and associated investments–when availability of statistical data allows. Probabilistic analyses capture the uncertainty and variability across a year with many possible combinations of load, generation, and power exchange considered. The limitations of only representing a small subset of expected operational snapshots are thus avoided, while enabling possible congestion in the grid to be estimated, in terms of duration and quantity, as well as quantifying the yearly energy production from each wind/PV power plant as well as the risk for the producer of being curtailed due to system or local constraints. Moreover, a probabilistic approach allows the consideration of uncertainty factors such as the forced outage of transmission equipment, generation units, and the variability of wind/PV 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 operational analysis for congestion purposes can also be performed.

In order to economically justify transmission investment, the profitability of individual transmission reinforcements needs to be assessed. The observed benefit arising from the difference in the marginal generation cost between the interconnected areas (low-cost and high-cost areas) needs to be greater than the annual capital and operating cost of the transmission reinforcement. Additional criteria can also be adopted such as environmental benefits, in terms of carbon dioxide emission reduction, social benefits, in terms of enhancing "social welfare" improvements in system losses, etc. An example set of criteria to assess the profitability of transmission reinforcements is presented in ENTSO-E (2011, 2016), as well as indexes that are quantitatively evaluated with and without additional wind/PV 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 16 where many combinations of load and generation using unit dispatch based on cost optimization are created and analyzed. For each combination, the branch loadings have been determined for normal and contingency situations. The criteria for prioritizing bottlenecks were developed together with a method for ranking them according to a risk-based severity index (Ciupuliga et al. 2012). By analyzing the risk of overload and the aggregated severity index, planners can decide whether bottlenecks are sufficiently severe or if they can be solved (temporarily) via operational measures.
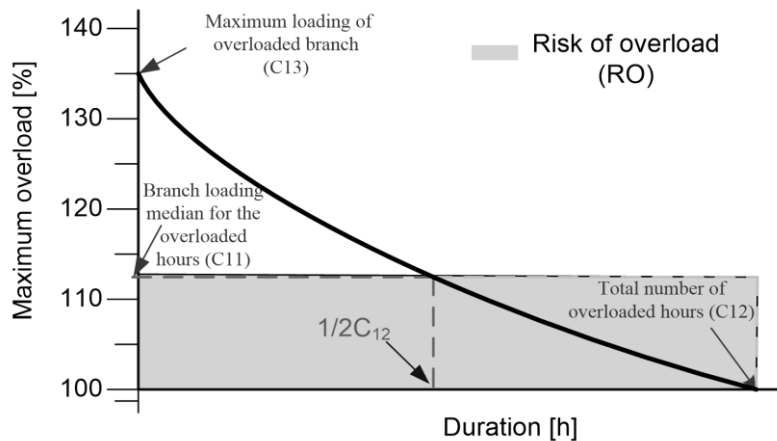
Figure 16. Maximum overload-duration curve for a branch during an N-1 scenario, highlighting criteria and risk of overload (Source: Ciupuliga et al. 2012)

Transmission capacity problems associated with wind/PV 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 maximizing the full use of existing transmission lines: using online information (temperature, loads/dynamic line rating (DLR)), using FACTS devices to control the power 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 lines with high-temperature conductors offers a still higher benefit but will be more expensive to implement.

It is also important to note that grid reinforcements should be compared against the option of curtailing wind/PV or adjusting the operation of other generation, in cases where grid adequacy is insufficient for only part of the time, or only for some production and load situations. Co-ordination of hydropower and wind/PV power in a region with limited export capability is another option which can reduce the need for grid upgrades (Matevosyan 2006; Tande and Uhlen 2004). Demand side management (DSM) that is controlled according to wind/PV production and transmission line loadings is a further option. The latter two strategies may be more beneficial than limiting wind/PV power as energy dissipation is avoided.

The above options can be viewed as forming an iterative loop back to changing operational practices and transmission grid inputs to the simulations. Despite considering wind/PV generation controllability, DSM, and other options, grid expansion and/or capacity reinforcement may become necessary, not only for cases of high wind/PV shares but also when it becomes necessary to extend the grid to remote areas to integrate important and proven wind/PV resources.

Confirming the transmission network design (upgrades) for the final volume of installed wind power has particular relevance for the case of offshore grid expansion planning. Offshore grids that interconnect several countries are associated with socioeconomic benefits due to 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 against 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. The highest socioeconomic benefit is defined in this context as the lowest operational plus investment costs for the entire system considered. Offshore grid expansion planning is a task that requires complex modeling, including offshore grid configurations (3E et al. 2011; NSCOGI 2012; PROMOTiON 2017). The required external inputs include detailed generation and grid data (capacity, costs, etc.) for the onshore grid, and offshore infrastructure cost data. A comparison between the benefits from direct connectors, tee-in connectors, or hub-to-hub connectors for the offshore transmission network is recommended. It should be noted that offshore grids usually develop in a modular way based on case-by-case investigations of potential hybrid projects, i.e., combinations of offshore wind and interconnection, as, for example, in the Kriegers's Flak project. Attempts to develop a masterplan for a larger area have been made, but they should be understood as an investigation of the overall potential (NSCOGI 2012; ENTSO-E 2014; ENTSO-E 2016).

6.5 Distribution Grid Studies

Barry Mather, Markus Kraiczy, Steffen Meinecke, Chenjie Ma, Martin Braun

Interconnection at the distribution system is often favorable (particularly for smaller systems) due to lower interconnection costs and more easily met system requirements. For studies where significant amounts of distribution-connected PV and wind are included, it may be beneficial to investigate the expected distribution system impacts. Distribution-connected wind and PV in aggregates needs to be analyzed, as outlined for the transmission system previously (see Section 6.3), but further impacts to the distribution system which they connect are also likely to occur.

In the distribution level, power flow analysis and short circuit analysis are widely used for wind/PV integration studies. However, with increased wind/PV generation and application of demand response units in the distribution level, the necessity for quasi-static time series (QSTS) simulations and dynamic stability analysis is also increased. The focus of this section is on distribution grids with a strong synchronous interconnection. For island grids and/or micro-grids, additional studies may be required. The following list shows different simulation methods and selected objectives of distribution grid integration studies.

- Short circuit analysis:
    - Protection studies
- Power flow analysis (snapshot):
    - Hosting capacity analysis (see Section 6.5.1)
    - Grid reinforcement analysis (see Section 6.5.2)
    - Contingency analysis
- Quasi-static time series analysis:
    - Grid losses analysis (see Section 6.5.3)
    - Voltage variability analysis and test of control algorithms (see Section 6.5.4)
    - Flexibility assessment of distributed energy resources (see Section 6.5.5)
- Dynamic stability analysis:

– Fault-ride through and anti-islanding detection studies
  – Development of dynamic distribution grid representations (see Section 6.2.2)

In this section, an overview of best practice examples for selected distribution study objectives is presented and high-level recommendations are derived. Hosting capacity analyses (see Section 6.5.1) are used to analyze the adequacy of the grid for particular PV/wind/load scenarios. This includes the maintaining of an acceptable level for the voltage magnitude, the thermal loading of grid assets, and the power quality in the distribution grid. In case the grid hosting capacity is reached for a defined wind/PV/load scenario, distribution grid reinforcement (see Section 6.5.2) may be required to ensure the adequacy of the grid for additional PV and Wind interconnections. The impact of distributed wind/PV integration on the grid losses can be studied by detailed grid losses analysis (see Section 6.5.3). Furthermore, wind and PV deployment affects the voltage variability in the distribution level and can affect the operation of voltage regulator. To ensure that existing voltage regulator (e.g., on-load tap changers, capacitor banks) are operating as designed and intended, a voltage variability analysis can be performed in the distribution level (see Section 6.5.4). Many other types of distribution studies including protection, reverse power flow, contingency analysis, dynamic generator response, unintentional islanding, flicker and harmonic studies, are also completed when necessary.

6.5.1 Hosting Capacity Analysis

Distribution-level power flow studies often aim to check the maximum amount of wind or PV on the existing networks without needing to complete any grid reinforcements. Often hosting capacities for circuits are computed to inform and screen wind/PV interconnections to eliminate the need to complete interconnection-specific studies until total generation has exceeded the precomputed hosting capacity. Note: the hosting capacity of a circuit is not the overall limit for wind/PV integration as grid reinforcement and other operational changes can be used to greatly increase deployable wind/PV level. Hosting capacity analysis results have been used to generate maps of entire regional distribution power systems, again to inform the interconnection process.

Certain salient operating conditions (including load, wind and solar generation) are investigated to estimate the impact of the proposed amount of wind and/or PV expected on an individual circuit (Seguin et al. 2016). The resulting unbalanced three-phase voltage profile is often the output, effectively bracketing the voltage profile envelope expected on the circuit for any operating condition. This envelope is then evaluated to ensure voltages on the distribution circuit are within acceptable limits for the entire range of expected operation. If voltage violations are found mitigation measures can be investigated and their costs considered to determine the least-cost mitigation strategy.

Different types of hosting capacity analysis are as follows:

- Deployment scenario independent hosting capacity analysis
- Locational hosting capacity analysis

Deployment scenario independent hosting capacity analysis provides the maximum amount of wind/PV that can be integrated on a circuit regardless of where the wind/PV interconnects to the system. This type of analysis usually uses 100s or 1,000s of deployment scenarios which are randomly determined and each deployment scenario is evaluated and graded for wind/PV impacts at increasing levels of wind/PV generation (Rylander and Smith 2012). The lowest level of wind/PV that causes a distribution circuit impact that is above the planning criteria

limits (e.g., a circuit overvoltage, thermal overload, etc.) within all the scenarios in this Monte Carlo method is selected as the hosting capacity of the entire circuit. This sort of hosting capacity is valuable when distribution utilities and developers are trying to inform the interconnection process of many wind/PV systems such as the interconnection of many residential roof-top systems (Smith et al. 2015).

Locational hosting capacity analysis simply computes the maximum wind/PV that can be interconnected at every modeled node on a distribution circuit (Rylander, Smith and Sunderman 2015). The additional of locational hosting information better informs where the interconnection of larger wind/PV systems will be easier. However, as soon as a wind/PV system is interconnected (or planned for interconnection) to the distribution system a new calculation of remaining locational hosting capacity must be completed in order to take into account the possible reduction of previous locational hosting capacities (i.e., as deployment scenarios change analysis needs to be repeated).

Additionally, there are two general methods for determining hosting capacity which are:

- Iterative hosting capacity calculations
- Streamlined/linearized hosting capacity calculations

Either calculation method can be applied to either deployment scenario independent or locational hosting capacity analysis. Iterative hosting capacity calculations simply increase the amount of wind/PV on a circuit, computing and grading expected circuit impacts at each generation level, until an impact that is higher than the acceptable planning levels is reached. This type of analysis can require considerable time and/or computational resources to complete due to the potentially large number of power flow solutions required. Streamlined/linearized hosting capacity calculations require less computational resources by effectively linearizing the power flow solutions in order to directly calculate the wind/PV generation levels at which unacceptable circuit impacts begin to occur. The increased speed of the hosting capacity calculation comes at the cost of potential error in hosting capacity numbers. Of course, the two calculation methods can be easily combined to provide relatively fast hosting capacity analysis and improved levels of hosting capacity accuracy if required.

6.5.2 Distribution network reinforcement

There are various reasons for grid reinforcement in the distribution level. The conventional reasons are high operational costs of grid assets, aging of grid assets, changes in planning and operation principles by the distribution system operator (DSO) or changes in the grid supply task. The integration of wind and PV, as well as increased distribution grid transit flows, can be a relevant driver for grid reinforcement in the distribution level, as discussed in this section.

A widespread and economically worthwhile strategy to handle overloading of grid assets or voltage violations is the so-called NOVA principle, which means grid optimization before grid reinforcement and before grid expansion. Therefore, operational solutions or reconfigurations within the existing grid infrastructure should be considered, before grid reinforcement or even grid expansions are implemented. However, the grid optimization potential is even for conventional grid assets multilateral and sometimes not easy to model. Therefore, many grid reinforcement studies neglect, or only partially consider, this first and very important step of the NOVA principle. Measures of grid optimization for example include: the adjustment of voltage regulator set points, the application of smart inverter function (if applicable), the relocation of feeder separation points, and adjustments of the MV/LV transformer tap position.

Example reinforcement measures for the NOVA principle include line and transformer replacements, e.g., the increase of the rated line/ transformer capacity.

Compared to transmission systems, distribution grid reinforcement analysis is less focused on-line conductor and tower configuration and optimization. Planning permissions for new lines are obtained usually much faster in the distribution level. However, because of simple protection coordination, a radially operated topology is usually a hard grid planning condition for medium and low voltage grids in many utilities. Figure 17 shows a simplified flow chart for distribution grid reinforcement studies.

Definition of future scenarios for load and (RES) generation

Regionalization of scenarios, e.g. via clustering

Grid data arrangement (preparate and validate real grid data, possibly derivate representative grids, determine future RES placement, etc.)

Definition of planning guidelines

Definition of optimization, reinforcement and expansion measures

Base case comparision to optimizations (e.g. Smart Grid technologies)

Extrapolation and monetisation of reinforcement measures

Derive recommendations for action

Figure 17: Flow diagram of system-wide distribution network integration study

In recent years, various system-wide network reinforcement studies have been conducted, to estimate the future power system reinforcement costs with increasing RES generation (Höflich 2012; Büchner 2014; Scheidler et al. 2018, 2016). These studies employ procedures similar to Figure 17. In the medium and low voltage level distribution grid reinforcement studies on a regional or system-wide scale are often performed on representative networks, due to the very large quantity of MV and LV systems (see Section 2.3.2). Therefore, the selection of the representative networks, e.g., via clustering, is a very sensitive and important task for the overall accuracy of the study.

In recent works by Scheidler et al. (2018, 2016), Thurner et al. (2018) and Braun et al. (2018), distribution grid reinforcement studies are conducted for a large quantity of real distribution grids (see Section 2.3.2 Distribution Grid Data). This approach requires comprehensive real grid information and a high degree of automation for data handling and grid simulation. This

approach can cover the very high diversity of distribution grids in detail and can potentially achieve a very high accuracy of the grid reinforcement studies.

Finally, when presenting the results, it is important to put the wind/PV integration driven reinforcement costs in contrast with generally necessary reinforcements, such as replacing outdated grid assets with new equipment.

6.5.3 Analyzing Grid Losses

The integration of distribution grid connected wind/PV and other distributed generators (DGs) also has a significant impact on the distribution grid losses. Grid losses are often considered as a key efficiency indicator of a DSO by regulators in different countries (ERGEG 2008). In addition, a reliable estimation of grid energy losses is of both technical and economic interest to DSO companies. In general, wind and PV power generation close to loads can decrease losses. However, due to the fluctuating generation pattern, wind/PV can impose extra loading peaks on low voltage (LV) grids, which lead to high losses, even at relatively low shares of generation. In the medium voltage (MV) level, reversed power flows from LV level as well as large generators may lead to either decrease or increase of grid losses. Therefore, the determination of grid losses for a large area can be highly complex.

Conventional methods for loss estimation, e.g., the application of loss formula (Gustafson 1989) and load profile-based method (VDEW 2000), are not suitable in current context due to the lack of consideration of DGs. Rao et al. (2006), compares the existing estimation results using loss formula against an extensive amount of measurement data on several typical LV feeders over long time. They further apply the measurement data in improving the loss formula parameters. This study gives a good practice in applying loss formula in the new context.

Marinopoulos et al. (2011) investigate the impact of DGs on grid losses based on stochastic models. By varying a parameter of installed PV plants at different penetration rates, as well as positions, a probabilistic model is created by combining the extensive stochastic modeling of PV and measurement data for the demand side. Annual power flow calculations are applied on models to determine losses of an urban radial distribution feeder. Results may be of interest for dimensioning, siting and cost allocation in distribution systems with DGs. In another study, Shulgin et al. (2012) take a close look on the impact of network configurations on distribution grid losses. A modified stochastic model is proposed in (Shulgin 2012), in which a power covariance matrix is introduced and investigated. Test results show that energy losses are determined with sufficient accuracy and reliability for practical purposes. This method is strongly relevant, when grid data are available.

In order to deal with a large amount of LV feeders, Heckmann et al. (2013) presented a strategy for determining distribution grid losses from a combined method of annual power flow simulation and statistical analysis. By detailed analysis of Geographic Information System (GIS) data, a large quantity of LV grids are classified by feeder length and weighted loads. Typical grids are further investigated in annual simulations. Energy losses of a large grid area are thus estimated by combination of typical loss behavior, grid features as well as allocated consumption and generations. Furthermore, the development of grid losses at MV level is exemplary studied on representative grid models. Dashtaki et al. (2013) present a loss estimation algorithm which uses a similar concept as Heckmann, et al. (2013), i.e., clustering LV feeders and detailed loss calculation of "average" feeders. Numerical simulation results show that the proposed algorithm gives an estimation of feeder losses with error of less than 10%.

In the following, we show recommendations and guidelines from the work of (Heckmann et al. (2013) as well as their recent methodological developments, for estimation of energy losses in distribution grids.

- Data collection:
  - Collecting all possible network data (e.g., from GIS database and/ or, grid asset database) as well as the generation and consumption information regarding to generation/ load tariff type, annual energy and geographical locations.
- Modeling:
  - Converting grid topologies from a GIS database into electrical power flow models.
  - Parameterizing electrical equipment e.g., transformers and lines, from real assets data.
  - Mapping of generation and consumption data to the grid model.
- Methodology:
  - Clustering distribution grids based on their characteristics (features), recommended methods: Principal Component Analysis, Neural Network, k-Means Clustering etc.
  - Extensive yearly simulation of certain amount of reference grids in each cluster, to determine typical grid losses for similar grids.
  - Simulation of additional grids for validation purpose; validation of clustering models by comparing simulation and estimation results.
  - Extrapolation of typical losses onto other grids in each cluster, accumulation of the results to the whole grid area under investigation.

This general approach can be further improved by integrating real measurement profiles or other control mechanisms. For instance, power measurement profiles in ¼-h resolutions provide more realistic behavior of large generators or consumers. By comparing power flows at the HV/MV transformer nodes, aggregated energy of generation and consumption at lower level grids can be validated. It can also be extended for discussing other research questions related to grid losses. Optimal DG sizing and placement strategy, which identifies the best positions for new DG units, can locally balance the generation and demand and therefore reduce losses. Demand side management (DSM) may coordinate and synchronize generation and demand temporally, so that transportation losses on feeders can be avoided twice. Other measures with an impact on grid losses, e.g., adjustment of grid operation voltage, active power curtailment, and reactive power provision of DGs, can also be addressed by further implementations.

6.5.4 Voltage Variability Analysis and Test of Control Algorithms

A Variability analysis of a distribution circuits operation over a relatively long period of time (e.g., a year) is completed to estimate the distribution-connected wind and/or PV's impact on automatic voltage regulation equipment. Such equipment (line regulators and switched capacitor banks as examples) is used widely in North America and increasingly used in Europe to manage distribution-system-level variability due to integrated PV. Gaining an understanding of how PV impacts the use and cycling of voltage regulation equipment is often the primary driver for voltage variability analysis due to the potentially shortened lifetimes of the equipment or requirement of more frequent maintenance if operated excessively due to variable PV generation and thus incurring increased operation cost.

Variability analysis study methods vary in complexity and accuracy. One relatively simple variability classification includes only the analysis of wind/solar resource data related to wind and PV generators connected to a distribution circuit (Mather, et al. 2014). In this case, the

resources of wind and/or solar are analyzed to determine the likelihood of large generation ramps (either loss of generation, return of generation, or both) over a time period. Then, considering the likelihood of such events, a level of loss/return of generation is chosen as the representative high-impact case (an event that has high impact but also happens often enough to be of concern for distribution-level power quality). Distribution power flow analysis is completed for these scenarios by simply translating resource variability to generating power variability using simply wind/PV system models and the voltage variations expected are calculated. If such voltage variations are extreme, resulting in over- or under-voltage situations, some level and form of mitigation is necessary as distribution utilities are required to supply voltage to customers within a specific voltage range. Further, if voltage variations are large enough (i.e., larger than half the voltage deadband of an automatic voltage regulation device) mitigation for potential over-operation of the device may be necessary. Such mitigation typically entails relocating the automatic voltage regulation device or changing its voltage control parameters.

More realistic variability analysis can be completed through the full-scale quasi-static time-series (QSTS) simulation of a distribution circuit over an entire year (Reno et al. 2017). In this case, time-aligned load and resource data at a relatively high temporal resolution are needed to effectively simulate the operation of the circuit. Variability analysis using QSTS simulations usually requires at least two yearlong simulations, one to set the baseline operational parameters and one to see how a proposed wind/PV system will impact the system. The overall number of automatic voltage regulation equipment operations over the simulated year is usually sufficient to determine the impact of wind/PV variability on the circuit. Additional metrics addressing other distribution voltage concerns, such as flicker, conservation voltage reduction, etc., can be calculated as well from the data collected during circuit simulation.

6.5.5 *Flexibility Assessment of Distributed Energy Resources and TSO/DSO Interaction*

In a power supply system with an increasing share of wind/PV in the distribution grid, there is a growing need for generators and demand response units to provide ancillary services or market flexibilities. Therefore, flexibility assessments are becoming of increased relevance also in the distribution level. For example, several studies (e.g., Marten et al. (2013), Ali et al. (2015), Kaempf et al. (2015), Wang et al. (2017)) analyze the potential of distributed generators to provide reactive power flexibility at the TSO/DSO network interface. Furthermore, wind and PV curtailment, economic dispatch and/or frequency control in the distribution grid will likely increase in power systems with a high share of distributed generation. Therefore, an improved coordination of transmission system and distribution system operation and planning is required, to access the flexibility of distributed generators and demand response units within the distribution level (see IEA PVPS TCP Task 14 Activity 2.7 and IEA ISGAN TCP Annex 6 activities).

6.6 Checklist: Network Simulations: Power flow and Dynamics

Checklist of Key Issues: Network Simulations: Power flow and Dynamics

6.6.1 Recommendations for Steady-State Analyses

Specific issues and recommendations regarding power flow simulations with wind and solar power include:

- *Creating a number of credible power flow cases*: snapshots chosen should include critical situations regarding wind and solar power, such as periods with high non-synchronous generation (wind, solar) and import via HVDC. This is in addition to the peak load and low load situations traditionally studied. The correlation between demand, wind and solar production, specific to a particular system or region, should be taken into account. An evaluation of the snapshot's statistical relevance is beneficial as an input to the cost-effectiveness of implementing corrective actions - for example as part of a multi-year analysis. Moving towards probabilistic analysis, a full year with cost benefit analysis is recommended for network reinforcement.

- *Deterministic steady-state security analysis*: in compliance with N and N-1 security criteria, power flow analyses are performed to identify transmission network bottlenecks (congestion), and to assess the system's ability to maintain the voltage profile.

- *Network loading (congestion) assessment*: network branch loadings should be determined for wind/solar generation and load combinations, across a year, both for normal and contingency (N-1) situations. Bottlenecks can be identified in a probabilistic manner, so that by analyzing the overload risk and the aggregated severity index, planners can identify whether bottlenecks should be considered severe or whether they can be solved (temporarily) via operational measures. A probabilistic approach allows uncertainty factors such as the forced outage of transmission equipment, generation units and wind and solar generation variability to be considered.

- *Time-series power flow and operation of discrete controllers*: reducing the number of online conventional power plants will also reduce the number of continuously acting automatic voltage regulators, unless the plants are converted to synchronous compensators. Wind and solar variability may require more frequent operation of discrete controllers, e.g., shunt reactors, with a detrimental effect on plant lifetime and the viability of such an approach.
    - Power transfer fluctuations on cross-border lines caused by the variable production of wind/PV power plants should be examined to help determine the steady-state cross-border transmission power margins (net transfer capacity, while taking into account wind/PV energy production).

- *Short circuit levels*: for high wind and solar shares of production, some synchronous generation will not be dispatched, which may lead to a reduction in the minimum short circuit level in some locations (the presence of wind and solar generation in other non-traditional locations may actually improve the fault level in those areas). This, in turn, may affect the power quality, voltage step changes after shunt switching and the operation of line commutated HVDC converters, leading to the mal-operation of protection systems.

- *Protection systems*: increased generation capacity at lower voltage levels may lead to reverse power flows from distribution buses (former load buses), such that correct operation of protection systems should be ensured.

6.6.2 Recommendations for Dynamic Analyses

- *Selecting snapshot cases for analysis*: A wide range of wind and solar share, as well as demand levels (recognizing the correlation between inputs) should be included to best understand the dynamic limits. The snapshots selected need not be the same as those chosen for steady-state power flow analysis. It is also important to set up the case carefully –not simply replacing the same volume of conventional generation online by the addition of wind/PV plant, as several (conventional) generators could be reducing their output but remain online. Understanding the new commitment and dispatch patterns with the addition of wind and solar is important and should be carefully considered when setting up the stability cases and interpreting the obtained results.
- *PV and wind turbine models:* Appropriate model complexity will depend on the study application. Using the short circuit ratio (SCR) to determine the strength of the system, guidelines for the proper models to be used in stability studies are provided: generic RMS models for *strong* systems; EMT models for *weak* systems; and manufacturer-specific detailed RMS models for systems of *intermediate* strength. Ideally, studies should be performed with different PV and wind turbine technologies, but often it is sufficient to utilize generic models that capture the minimum performance required in the connection code.
- *Model validation and verification*: Validation of all models (conventional generators, PV and wind turbine, and load) is important. PV and wind turbine models should recognize (evolving) technology capability and grid code requirements in order to simulate PV and wind turbine capabilities in a relevant way for the system in question.
- *System stability:* Different systems may experience totally different dynamic issues (e.g., frequency stability, voltage stability, or transient stability challenges), dependent on the underlying correlation between wind/PV production and system demand, the underlying flexibility and capabilities of the conventional generation portfolio, relative location of generation assets and major load centers, etc., implying that specific system studies may be required.
- *Wind turbine/PV controls*: Studies should recognize that wind turbine/PV controls, as part of a coordinated control strategy(s), may offer system advantages. VSC-HVDC can, to a certain extent, also be used for system stabilization.
- *(Dynamic) load modeling*: With increasing shares of wind and solar generation on the distribution network, and power systems becoming 'lighter' due to the displacement of conventional generation (reduced inertia), load characteristics will more strongly influence system performance. Existing load models should be re-evaluated, including frequency and voltage sensitivities, and the time varying nature of the load composition, and hence the load models themselves, should be considered.
- Transient stability analysis:
  - It can be important to include the effect of protection devices for both network and converter-interfaced generating equipment; however, boiler/steam turbine models are not required. Protection relay settings should recognize changes in the dynamic response of the system, and respect any dynamic operating criteria (e.g., frequency variation range) adopted by the local TSO. The ability to ride through multiple voltage dips within a certain period may also need to be addressed.
  - Wind and solar generation can provide system support during voltage dips, and help to dampen oscillations, although the level of support provided is network sensitive, and the capability may also vary depending on the priority given to active or reactive power recovery. Proper representation of the impedance connecting the wind farms is crucial within simulation studies.

- To mitigate any issues discovered, fast acting reactive power response devices during and following disturbances can be applied, e.g., installing FACTS devices, synchronous compensators, and/or requiring all wind plants and conventional generators to incorporate that specific capability.

- *Voltage stability studies:* At low wind/solar shares it is probably unnecessary to perform studies, as system stability is likely to be unaffected or even enhanced by the presence of wind turbines/PV panels. This argument is particularly true if the reactive power control capabilities of the wind turbines (PV) are deployed to manage voltage, and if they are connected at transmission level.
  - As conventional generation is displaced at higher shares of wind and solar, voltage security levels may be affected in certain locations, and so requiring more detailed analysis.

- *Frequency stability studies:*
  - The fraction of generation participating in governor control is a good metric for the expected performance. The maneuverable capacity of such generation is also important, with resources providing significant incremental power in order for the frequency to return to its original working point. Particularly for larger systems, the self-regulating effect of the load can also ameliorate severe disturbances: simulation results can be sensitive to how the load is modelled.
  - Modeling 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. Reduced inertia at times of high non-synchronous (wind, PV and/or HVDC input) shares will alter the system response for both faults and contingencies, particularly for smaller power systems.
  - A reduced network representation may be sufficient, focusing on demand-generation imbalances and active power flows, with reduced consideration of voltage variations and reactive power requirements. However, under-frequency load shedding can provide system support during frequency drops. Proper representation of the frequency disconnection rules, as stipulated in the national Grid Codes, is crucial for such studies.
  - Wind turbines can provide a fast frequency response, depending on their operating point, and PV plant can provide a similar response if their output has previously been curtailed. Fast-acting load response or storage may also be included.
  - Mitigation measures include disabling/replacing aspects of distribution connected protection schemes for wind plants, while 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 change of frequency should be reviewed.
  - It is important to set up the case carefully and not replace the same amount of generation online as added wind/PV, as several generators can reduce their output while online. Understanding the new commitment and dispatch patterns with the addition of wind and solar is important and should be used to set up the stability cases.

- *Small-signal stability studies:* Wind and solar generation do not generally introduce small-signal oscillatory modes, but as their presence may displace conventional generation (and associated power system stabilizers), and alter the magnitude and direction of transmission line power flows, it follows that small signal stability may be impacted.

- *Sub-synchronous oscillations*: Sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI) should be investigated as part of small-signal stability analysis, particularly in relation to doubly fed (type 3) wind turbines. A range of mitigation measures including bypass filters, FACTS devices, and auxiliary (damping) controls are available.
- *Common-mode fault events*: Network faults and/or loss of a major infeed can result in widespread voltage depressions and/or large frequency deviations and the common-mode tripping of local wind and solar generation. Consequently, the operation of associated protection systems may play a crucial role in determining system outcomes, requiring sophisticated modeling methods. Delayed active power recovery from grid code compliant generation following a widely seen network fault may similarly lead to a common-mode power reduction and frequency stability issues - voltage dip induced frequency dips.

6.6.3 Recommendations Distribution Grid Studies

- *Overlap and coordination with transmission grid studies:* The scope, tools and methodologies for distribution grid studies will continue to expand and develop. A major driver is the integration of wind and PV systems at the distribution level, which entails both challenges and opportunities for distribution grid planning and operation. Stronger coordination of transmission and distribution grid studies will be required with higher shares of wind/PV to access the full capabilities and flexibilities of distributed resources for the overall bulk power system.
- *Distribution Grid Reinforcement Analysis*: A comprehensive catalogue of grid planning measures should be considered as part of the grid reinforcement analysis, i.e., grid optimization, before grid reinforcement, before grid expansion. Based on available input data and the scope of the study, the analyses can either be performed using representative or actual grid data, if available. For comprehensive system-wide distribution grid studies, a high degree of automation for data handling is required and recommended.
- *Grid Losses Analysis*: a detailed study of the grid losses for a certain number of reference grids, which represent other distribution grids, combined with statistical analysis or data-driven methods is recommended to cover for large variation in the network characteristics of distribution grids. It is also essential to consider both the location and generation pattern of wind/PV when representing distribution grids, as they both have a significant impact on the grid losses. In order to partially validate the implemented model of the grid area, the energy flow in the studied grid area can be investigated in comparison with real measurement data available at transmission level bulk supply points.

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7 Analyzing and Presenting the Results

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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 neighboring system then this will have an impact on reserves, voltage levels, economy of other power plants etc. Integration studies should be performed for any changes in the system to see the whole perspective. Here we mainly discuss the specific case of wind/PV power integration, but the same methods could be used also to study other changes in the system. If wind/PV power is compared with other investments, then an integration study should also be performed for the other alternative.

When analyzing simulation results, it is possible to iterate back to earlier stages in the flowchart (Figure 18), including rethinking initial assumptions. If the impact of wind/PV 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/PV integration study purpose and the main setup chosen will have crucial impacts on the results.
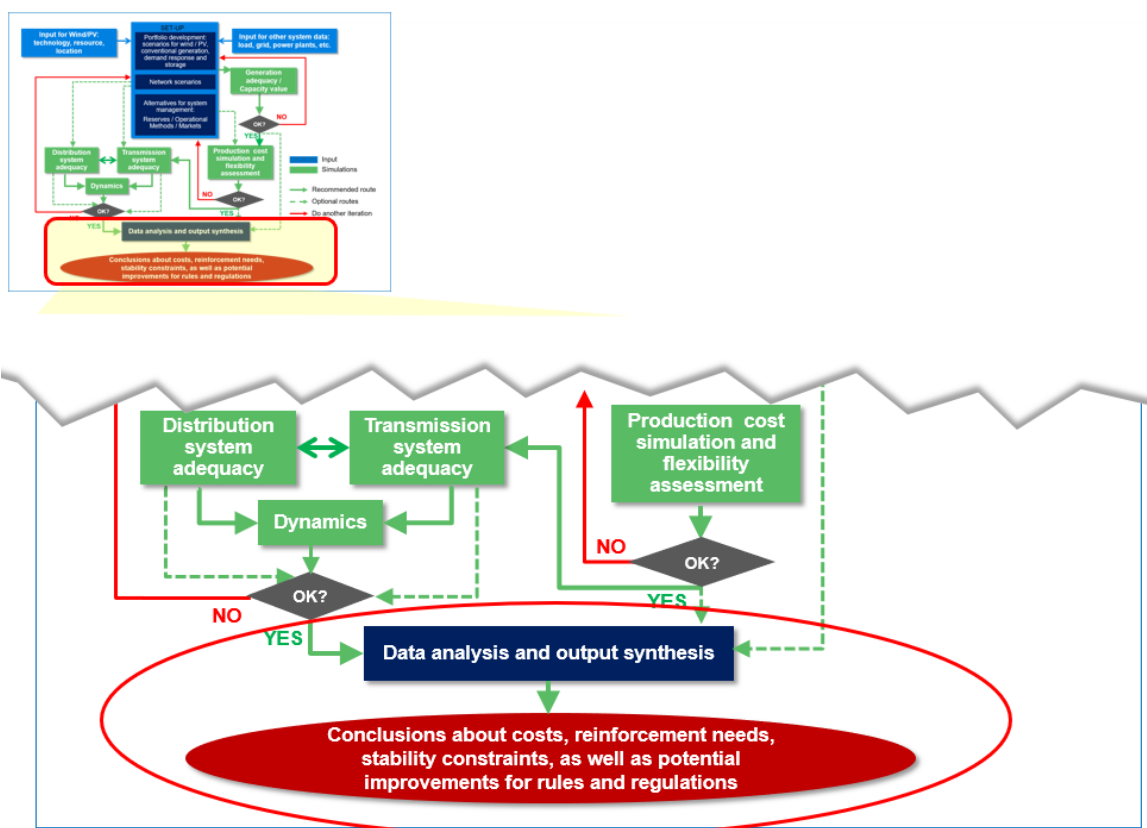
Figure 18. Wind/PV integration study components: data analysis and output synthesis

Main assumptions regarding access to enablers like flexible transmission to neighboring areas, flexible generation, or demand assets will influence the results. Both technical flexibility of power plants and demand side, as well as operational flexibility of management of system operation can change for future systems. At higher shares, the methods and tools used for

planning and operation, like allocation of reserves, need to be adapted. Successful wind/PV integration means changing the operation of the power system from how systems have been traditionally operated. Energy system integration (electrification from heat and transport sectors and power to gas options) will also bring new flexibility possibilities.

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/PV share 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.

This section starts with general discussion about the challenges of determining integration costs. The impact of wind/PV power on transmission/distribution 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. Main differences of wind and PV in integration studies are listed in Section 7.4. How to present the results with a list of limitations in the assumptions is discussed in Section 7.5.

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/PV power. This cost consists of the increase in the use of operating reserves and the balancing (market) that is used to maintain the system balance. Integration costs do not include the costs for installing new power plants (capital costs) and connecting them to the existing grid. Transmission/distribution grid expansion or reinforcement may also be needed, above the cost of connecting wind/PV power to the grid. In some studies, grid reinforcement costs are considered as part of integration costs.

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

- Integration cost should in principle be possible to calculate for any power system investment (e.g., power plant or 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). Stark (2015), develops a consistent framework for integration costs of many aspects of the power system in addition to wind/PV (Stark 2015).
- 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/PV power, the composition of both existing plants and additions will significantly influence the ability of the power system to integrate wind/PV 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/PV power. The approach usually taken in wind/PV 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/PV integration, it is relatively straightforward to assess the total operational cost for both no-wind/PV and wind/PV cases, and these operational costs can be compared. One can try the Put In one at a Time (PINT) or the Take Out One at a Time (TOOT) approach (ENTSO-E 2016). Here the challenges lie in how to choose the non-wind/PV case to be able to extract the wind/PV-induced costs only. In the case of transmission costs induced by wind/PV 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/PV power only is not accurate. ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects (CBA 2.0) addresses this issue (ENTSO-E 2015).

Integration costs of wind/PV power should be compared to something, like the production costs (levelized cost of energy LCOE) or market value of wind/PV power, or integration cost of other production forms. A fair comparison between power systems with differing amounts of wind/PV power should in principle have systems with the same reliability but also common levels of carbon dioxide emissions or at least take the CO_2 emission costs into account. The value of the capacity credit of wind/PV power can also be stated and considered when the amount of required total installed capacity is to be calculated.

Also, the value of wind/PV over the year is an important information. One way of doing this is by calculating the weighted average price being paid in the market (spot-market) for wind or PV (excluding any substitution). A relative high price compared to e.g., weighted average market price paid by demand is a measure of "good integration" and vice versa.

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

7.2 Impacts on Networks: Losses, Bottleneck Situations, and Reinforcement Needs

The impact of wind/PV power on transmission/distribution 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/PV power production can bring about power losses or benefits and changes in bottleneck situations. Depending on its location, wind/PV 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/PV plants relative to load and other generation will increase or decrease the grid 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 years with hourly resolution.

Results from power flow simulations (see sections 6.2 and 6.4) will reveal the need for transmission reinforcements. If transmission adequacy needs associated with wind/PV power integration are of concern for only a small fraction of the year, network investments can potentially be postponed using, for example, curtailment, re-dispatch, dynamic line ratings or topological modification to increase transmission line capacity. Also, co-ordinated control using FACTS devices or VSC-HVDC or demand response can be used. For these analyses also, more simulations than just a few snapshots are needed.

Transmission cost is the extra cost in the transmission system when wind/PV power is integrated. Either all extra costs are allocated to wind/PV power, or only part of the extra costs are allocated to wind/PV 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/PV power (e.g., on a $/MW or $/kWh wind/PV basis), one should be aware that due to the large amount of location and time-specific conditions, they cannot be directly compared from plant to plant or from country to country. Grid reinforcement needs and costs will depend on where the wind/PV power plants are located relative to load and grid infrastructure. In addition, costs are dependent on the "grid situation" at the time the generator is connected. The same wind/PV power plant, connected at a different time, may lead to different grid reinforcement costs. Moreover, the grid reinforcement costs ($/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/PV on transmission losses and grid bottleneck situations. Economic planning of transmission network with wind and solar need to capture the whole picture— 8,760 hours of power flow with cost and benefit analyses.

7.3 Wind/PV 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 (unit commitment 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/PV 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 marginal cost of wind/PV 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/PV itself (Munksgaard and Morthorst 2008; Göransson 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/PV energy shares 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 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/PV power integration. Basically, there will be two simulation runs, to be able to subtract the costs and get a proxy for wind/PV integration cost.

The total costs for power systems may increase due to wind/PV power, but the operating costs of power systems will be reduced due to the use of wind/PV power. This is because the bulk of operating costs come from fuel costs and wind/PV 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/PV power.

One attempt of capturing cost of variability is by comparing simulations with flat wind/PV energy to varying wind/PV energy (EnerNex 2006; Meibom and Weber 2009 for wind power). 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/PV power integration costs (an example can be seen in AIGS 2008 for wind power). Different portfolios of generation mix, with different amounts of wind/PV 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/PV into the power system. Also cost-benefit analysis work is emerging. The benefit when adding wind/PV power to power systems is reducing the total operating costs and emissions as wind/PV replaces fossil fuels.

Studies are evolving from plain impacts and cost estimations to include value and cost, as well as different enablers like flexibility. Energy storage is emerging as one possible source of flexibility enabling higher shares of wind/PV, and as such it has become part of the analysis. Overall, one should consider what forms of flexibility are relevant to consider in the time scale of the study, taking into account the cost of flexibility. Storage will bring an extra layer of uncertainty and complexity in the simulations.

Regarding wind/PV 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/PV power may be supplied by conventional generators that are used to supply energy in the non-wind/PV case, and are used to supply less energy and more reserve in the wind/PV case. This is a critical distinction, and failure to understand this basic principle can lead to erroneous statements. During times when wind/PV power output increases, other generating units must back down, allowing them to provide up-reserve if needed.
- A wind/PV 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, gate closure times, bid size and availability.
- Capabilities to provide reserve from wind and solar power plants should also be taken into account as they can usually provide down-regulation. With larger shares of wind and solar, their generation may be curtailed at times. This opens possibility to provide reserve from wind and solar power plants, as operating in de-loaded mode gives room for providing both up- and down-regulation.

Regarding balancing on a longer time scale, reflecting the adequacy of power systems during peak load demands, the capacity value of wind/PV 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 shares (Holttinen et al. 2009). For PV, the daily energy is spread only to a 5- to 19-hour period (depending on season and location). Concentrating the generation to fewer hours causes the incremental capacity value of PV to decrease at a faster rate than the incremental capacity value of wind power in most locations, even as total capacity increases. Increases in wind capacity, particularly at lower shares, tend to smooth overall wind power in the aggregate. On first order, this tends to provide a greater proportion of capacity at peak capacity times than the incremental increase in solar PV capacity (Madaeni et al. 2012).

Some studies have introduced the capacity cost of wind power as integration cost. 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 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. 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.

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 automatic generation control (AGC), which is another needed service. Yet these units are not liable for providing AGC to the system (Milligan et al. 2012). Ancillary services are needed by the system, and but not all power plants need to provide all services.

Comparing total costs for different future power systems, including both investments for capacity and operational costs, gives a more holistic view of the costs and is easier to compare.

7.4 Main Differences Between Wind and PV in integration Studies

Data resolution: The spatial and temporal resolution of the data should match the intended goals of the study and the resolutions utilized in the power system simulations. Because of wind's more varied output over even relatively small regions, the spatial resolution of wind datasets may need to be higher than the resolution for PV. However, the temporal resolution of PV resources may need to be higher than wind due to the speed of the physical processes involved (like clouds), although this will depend on the size of area (wind turbulence can be fast in smaller areas).

Years of data needed (differences between years): Rare, but important, resource-driven events (i.e., fast-moving weather fronts across a large area) are less predictable for wind than PV. An integration study may need to include longer periods of time in order to appropriately capture the impact of such events.

Measured versus simulated data: use of satellite and NWP data is easier for PV. Oftentimes, the "clear-sky" pattern of solar power output is used for simulating solar forecast data. This can have implications on short-term (hour-ahead) forecasts in integration studies. While wind studies often rely on the persistence method, a modified "persistence of cloudiness" method should be adopted for solar power, to account for the diurnal patterns that are known a priori.

Controllability of wind/PV power plants: Solar PV is often installed in smaller capacities. It is more likely to be connected at lower voltage levels and more dispersed than wind power. This usually complicates getting real-time measurement data (less observability of changing output), as well as the possibility to control the output from system operators if needed. This results in two categories of solar PV being considered: distributed PV, which only modifies the net load shape; and utility scale PV, which the system operator can control for curtailment or reserve purposes. This is also valid for smaller wind power projects. However, new wind power

plants typically connect at higher voltage levels in distribution or transmission grid and are often both visible and controllable by the system operator.

The solar generation diurnal pattern creates well-defined times of additional flexibility requirements within the power system, with more downward capacity needed in the mornings as PV power picks up and more upward capacity needed in the evening as PV production drops. Due to the predictability of these patterns, the economic and reliability impacts can be mitigated through good operational practices like dynamic flexibility reserve requirements.

While wind power can potentially generate during any time of day, solar PV output follows a clear diurnal trend, with generation occurring only during the daytime. This has implications on a number of fronts, including: morning and evening ramping requirements, dimensioning system inertia forecasting needs, the location of the generation in the power system, capacity value calculations, and the expected timing and volume of curtailment.

Since the same weather processes drive wind power, solar power, and load, it is key that this data is co-incident to ensure the capture of the interactions and temporal correlations. When data is simulated for future sites where measurement data does not currently exist, it is best if these datasets are generated from the same numerical weather prediction model (NWP) runs. This ensures that the physics of the atmosphere is consistent for both generating technologies, and it helps to avoid erroneous ramps in the power output that may arise from ad hoc time series creation methods.

7.5 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. Comparisons with different power systems should also be made with care, as different systems have a different starting point and ability to integrate variable generation. 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:

- *Share of wind/PV power studied:* The share of wind/PV power can be expressed by various measures. Often either energy or capacity metrics are used: wind/PV power production as a percentage of gross demand (energy) and wind/PV power capacity as a percentage of peak load (capacity). However, these measures neglect the presence of interconnecting capacity with neighboring countries, although the cross-border interconnections are often the key to efficient power system operation. In particular, for the case of high wind/PV and minimum load, transmission-level operational constraints may be alleviated through utilizing cross-border transmission capacity for export of (excess) generation. It is thus relevant to express wind/PV share in terms of wind/PV capacity in percentage of the sum of minimum load and cross-border capacity.
- *Power system size and general characteristics:* Power system size as peak load and general characteristics like thermal/hydro dominated and the amount of flexible/inflexible units.
- *How wind/PV power is added:* What are the differences in scenarios for wind/PV and non-wind/PV cases?
- *Basic assumptions regarding flexibility, interconnection, operational practices.* The results regarding curtailed wind and solar indicate some lack of flexibility in the power system. All flexibility related inputs to the study will influence this result.

- *Method and simulation tool limitations.* The checklist of recommendations in this report can be used to benchmark the method used in the study.

Many wind/PV 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/PV or per megawatt-hour of total consumption (reflecting the increase in consumer price). There are also results as a percent of more wind/PV 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 useful to mention curtailment of wind/PV explicitly in final results. The net generation of wind/PV power is relevant. Curtailed amount can be used for example regarding transmission investment decisions.

Novel, emerging methods for presenting the results of larger studies are very useful in illustrating the changes in power exchanges and dispatch situations with large amounts of wind and solar (Bloom et al. 2016) and visualization invisualisation at www.youtube.com/watch?v=jx9_4GNkbIQ.

7.6 Study Limitations Arising from Assumptions

The results of a study will depend on assumptions and modeling 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 the uncertainty in the basic scenario concerning units and loads and prices in a future system when higher amounts of wind/PV power will happen. It is important when conclusions are drawn to consider the consequences of the assumptions chosen. Because not all wind/PV 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/PV power, where the remaining system is the same, the prices (set by marginal costs) will be lower in the system with wind/PV power, since units with highest marginal costs will be replaced when there is high wind or/and solar generation. 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 2). Making a generation expansion plan before the wind/PV 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/PV integration is not feasible. Another example is that large amounts of wind/PV power will result in more volatile prices (high prices during high load/low wind/PV, low prices during high wind/PV/low load), which in reality will result in changed

behavior of consumption and investments in flexible power plants and/or transmission to neighboringsystems. 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/PV power is added as an energy source only, or whether the wind/PV 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/PV power data; source and method used to simulate wind/PV 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 neighboring systems modelled
- Level of detail on modeling 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/PV plant controls are allowed to provide for ancillary services from wind/PV plants and the impact that has on integration

Enablers for cost-efficient integration of wind/PV power include flexible intra-day markets, use of continually updated wind/PV power forecasts, flexible trading with neighboring systems, efficient treatment of the limiting effect of handling large geographical spreading of total wind/PV 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 (Table 5). The following summary of different issues to be considered comes from the Task 25 summary report (Holttinen et al. 2009).

Table 5. Summary of issues/possible limitations in integration studies

Set Up		
A	Aim of Study	1 what happens with x GWh (or y GW) wind/PV 2 how much wind/PV is possible 3 other:
M	Method to Perform Study	1 add wind/PV energy 2 wind/PV also replaces capacity 3 load is increased same amount of GWh as wind/PV 4 optimal system design 5 other: For capacity credit also: (a) chronological, using wind/PV 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/PV 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 neighbors, historical market prices 3 perfect market simulation (each actor maximizes 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 behavior depending on the market prices) 5 other:
D	Design of Remaining System	1 constant remaining system 2 optimized remaining production capacity 3 optimized remaining transmission 4 changed operation due to wind/PV power 5 perfect trading rules 6 other:
Uncertainty and Balancing		
I	Imbalance Calculation	1 only wind/PV cause imbalances 2 wind/PV+ load forecast errors cause imbalance 3 wind/PV+ 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/PV forecasts: (a) assume no knowledge and large margins for wind/PV 0…full capacity, (b) assume perfect forecast for wind/PV, (c) persistence forecasts for wind/PV, (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 Modeling	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 optimization considered 6 limited, deterministic run-of-river 7 interaction with hydro resources not significant 8 other:
T	Thermal Power Modeling	1 ramp rates considered 2 start/stop costs considered 3 efficiency variation considered 4 heat production considered 5 other:
W	Wind/PV Power Modeling	1 time series: (a) measured wind speed + power curve (how many sites)/measured solar irradiance + PV system azimuth and tilt (b) wind power from wind power plants (how many sites)/PV power from PV plants (c) re-analysis wind speed + power curve (how many sites)/satellite-derived solar irradiance + PV system azimuth and tilt (d) time series smoothing considered (how) 2 wind/PV power profiles: (a) climatic, e.g., lowest/highest temperature, (b) hour of day, (c) season, e.g., only winter, (d) load percentile 3 coincident wind/PV data with load or not 4 installation scenarios for future wind/PV power distribution (put together scenarios by association, government plans; according to projected regional capacity factors…); specify geographical distribution of wind/PV 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).

7.7 Checklist: Analyzing and Presenting Results

Checklist of Key Issues: Analyzing and Presenting Results

- If the results show unexpectedly high and costly impacts of wind/PV 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 share of wind/PV, size and type of power system and the main assumptions and limitations arising from these.

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8 Conclusions and Future Work

Wind/PV 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/PV 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/PV plant size and location
- *Wind/PV power related data:* detailed wind/PV production data that correctly characterizes plant performance and geographical spread, co-incident with load data, as well as data on wind/PV and load uncertainty (forecast errors). Location of wind/PV 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, CO_2 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/PV power on short term reserves as statistical data analysis
- Running generation capacity adequacy analysis (resource adequacy) to assess capacity value of wind/PV power
- Running production cost simulations to see how wind/PV power impacts the scheduling and dispatch of conventional generation, and operational costs of the system
- Running network simulations to see that the network is adequate
- Running iterations based on initial results if there is need to change the generation or transmission portfolio or operational practices
- Analyzing the data and presenting the results

Depending on the shares studied, some components of the study can be omitted. How low share 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/PV resource, challenging high share situations can occur already before 10% of yearly share in some systems. To start with, at lower shares, portfolio development can just include the power system as it is operated today, and the main simulation components are production cost simulation and power flow, to see the impact of wind/PV power to the other power plants as well as needs to upgrade transmission network. Impacts to reserve requirements may also be addressed. For higher shares 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/PV power is usually not critical at low shares, 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/PV power into account as well as how to model the system to capture wind/PV 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/PV 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/PV case such that the differences are due to wind/PV addition only.

Integration study methodologies continue to evolve and new experience of real wind/PV integration will emerge. Recommendations for the main steps and methodologies will be updated as part of continuing international collaboration under the IEA Wind TCP Task 25 and IEA PVPS TCP Task 14. 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/PV 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 share wind/PV cases and in weak grids, as well as methodology for the emerging 100% renewables studies. Future grids with more DC transmission.
- Implications of market design and/or regulatory processes for wind/PV integration—it is not now well-known how markets should be designed to incentivize flexibility and generation resource adequacy in systems with high wind/PV shares; regulatory processes for investment cost recovery are critical to success. There is also a need for studies on how large amounts of wind/PV power impact different market elements so that market integration strategies or alternative market designs can be recommended. Markets should also enable effective use of wind/PV capabilities for power system support (for example when running in curtailed mode). 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.

As energy continues to transition towards renewables and wind and solar become mainstream, integration studies will become general power system design studies at very high wind and solar shares. At some point, integration studies will become standard power system design studies.