Recommended Practices for wind and solar integration studies

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Abstract

IEA TCP WIND Task 25 ”Design and Operation of Energy Systems with Large Amounts of Variable Generation” has compiled Recommended Practices for power system impact studies, commonly known as wind and solar integration studies. It provides research institutes, consultants, and system operators with the best available information on how to perform an integration study. It is also useful in benchmarking any integration studies: the recommendations check list can be used to identify what has and has not been taken into account. The latest update, to Edition 3, includes recommendations for very high wind and solar shares– wind and solar dominated power systems, with sector coupling and energy system integration.

1. Introduction

This paper summarises the Recommended Practices for Wind/Solar Integration Studies of IEA Wind TCP (Technology Collaboration Programme), working together with IEA PVPS TCP on solar energy in power systems. The purpose of the Recommended Practices report is to provide research institutes, consultants, and system operators with the best available information on how to best perform a wind/solar photovoltaic (PV) integration study. With increasing wind and solar deployment and tremendous future potential, it is crucial that commonly accepted methodologies are applied to accurately assess integration issues and to reduce uncertainties surrounding the impact(s) of renewable generation.

The integration studies, first conducted for wind and solar generation separately, have evolved towards examining the integration of wind and solar generation 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 generation on the grid, and on the operation of power generation. The characteristics of the power system being studied, and the data available, can vary significantly. In addition, goals and approaches can differ, and thus the results can be difficult to compare. The methodologies used in most studies are diverse and are still evolving, especially for wind and solar dominated power and energy systems.

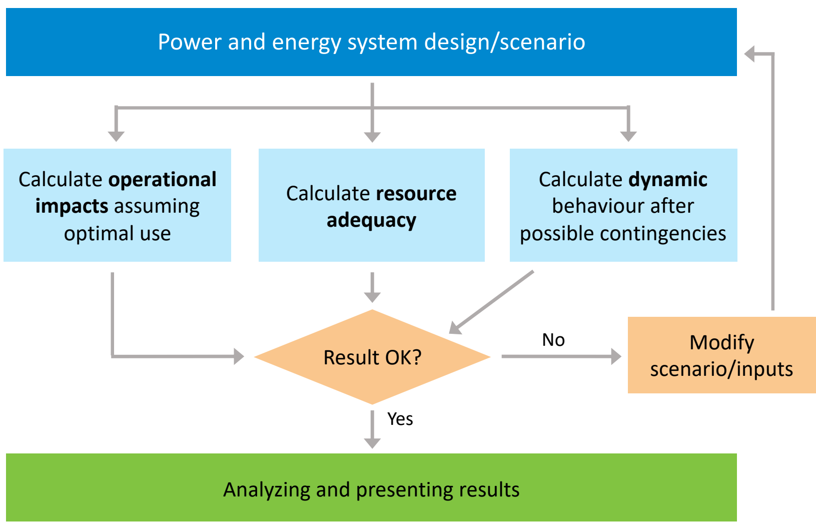

Figure 1. Flow chart for a full wind/solar integration study.

The Recommended Practices RP16 Ed.3[1], published in 2024, updates the findings regarding how to study the consequences of small and medium shares of wind and solar generation (<50% of demand) from RP16 Ed 2, while outlining challenges and solutions to study impacts of very high wind and solar shares. The report does not include any results of studies, which are published separately as summary reports [2]. The recommended practices reports are available at https://iea-wind.org/iea-publications/.

2. Approach

Phases of a complete integration study are illustrated using a flow chart (Figure 1). Recommended Practices follow this flow chart, giving recommendations for each of the phases.

Beginning with a base case scenario for the power and energy system in question, its technical feasibility will be analysed through the different parts of a complete study, considering operational/balancing issues, system adequacy, and system dynamics, among a range of analysis phases. It is important to highlight the importance of iterations in the integration study setup. In addition to iterations back to the initial scenario assumptions – from the three feasibility checks for Operation, Adequacy, and Dynamics – iterations between network simulations and production cost simulations may also be needed, especially for network dynamics with higher wind and solar shares.

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

- Study objective: What is included and what is excluded – neighbouring power systems and links to other energy sectors including new kinds of demand, such as power2X.
- Power and energy system data: Includes power plant and storage data, load data, transmission network, operational practices including market structures, and coupling to energy sectors linking available flexibility, such as heat.
- Wind/PV power related data: Detailed wind/solar generation data that fully characterise plant performance and geographical spread (co-incident with load and all weather dependent data used) as well as data on wind/PV and load uncertainty (forecast errors) and the location of wind/PV power plants for grid simulations.
- Other assumptions that play a key role in results: Links to other energy sectors, such as heat, transport, and gas; demand flexibility; scenarios of (future) conventional generation; storage and network characteristics; as well as fuel prices, taxes, CO_2 allowances, and emission limits.

Key tasks that comprise an integration study include the following:

- Scenario setup including base case for comparison: For future systems, this will entail capacity expansion models.
- Data collection and quality checking.
- Operational impacts: Running production cost simulations to see how wind/solar power impacts the scheduling and dispatch of generation and storage, activation of demand flexibility, and estimating the system operational cost. Need for flexibility from other sources (generation, storage, demand). Impact of wind and PV generation on short-term reserves as part of statistical data analysis.
- Adequacy impacts: Running resource adequacy analysis to assess whether reliability targets are met. Running (steady-state) network simulations to determine whether the network is adequate, or where reinforcements and/or changes in security architecture or network operational processes are needed.
- Impacts on system stability: Running dynamic simulations to ensure that power system stability is adequate, i.e. the studied power system can handle possible contingencies.
- If results achieved are not considered satisfactory: Changes should be applied to the generation, storage, or transmission portfolio, or operational practices, including demand flexibility (an iterative process).
- Analysing the output data and presenting the results.

Depending on the wind and solar shares studied, some components of the study can be omitted. To begin with, at lower shares, scenarios studied need only include the power system, operated based on existing practices. The impact of wind/PV power on other power plants, as well as on the need to upgrade the transmission network, are the main issues to assess with the main simulation tools (production cost simulation and power flow). Even if the capacity value of wind/PV power is usually not critical at low shares, it is often included in such studies. In addition, in many studies, the transmission network is not studied in detail, and a simplified approach is applied as part of production cost simulations.

For higher wind and solar shares, it will become important to assess more detailed operating reserve and other grid service needs and their provision, such as through a detailed flexibility assessment. Finally, for wind and solar dominated systems, resource adequacy and stability aspects become crucial to study in (great) detail. The power system transitions from one that is largely based on dispatchable synchronous-machine-based generation to one that is based on power electronic interfaces (for both generators and loads), with a dramatic reduction in the number of synchronous machines, and the addition of new load types and sector coupling. Assessing high wind/PV shares usually requires conducting studies projecting 10–30 years in the future. Such simulation results can illustrate ways to prepare for the possible impacts of adding wind and solar generation. The results can show how changes to operating procedures, network code requirements, and market structures can help to ensure reliable and economic operation.

When projecting beyond 10 years, other changes, such as electrification impacts, will be important to incorporate, with increased coupling to other energy sectors changing the passive load paradigm and increasing different forms of storage for flexibility purposes.

Integration studies are focussed on future scenarios, and thus they form part of the planning phase, and are not operational, real-time tools for system operators. Recommendations are given as major points to consider when wind and solar PV generation is included in simulation analyses, in terms of power flow and dynamic/transient studies, and detailed recommendations on transmission planning are not included.

3. Recommendations for Input data and Power and Energy System Scenarios

3.1. Input data

The recommendation checklist for input data is summarised in Table 1.

Table 1. Recommendations for Input data for wind/solar integration studies.

	Resource Adequacy/ Capacity Value	Capacity Expansion Model	Unit Commitment and Economic Dispatch (UCED) including reserve requirements	Power Flow	Dynamics
Wind/PV	Hourly time series capturing locational smoothing of large-scale wind/PV, representative of wind/PV power variations and time-synchronised with load data*. 30+ years of data	Hourly time series capturing locational smoothing of large-scale wind/PV power, representative of (correlated) wind/PV power variations and synchronised with load data.*	5-minute to hourly time series of at least 1 year capturing locational smoothing of large-scale wind/PV power, representative of wind/PV power variations and time-synchronised with load data.*	Wind/PV capacity at nodes, generation and load snapshots relevant for wind/PV integration, 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 for traditional resource adequacy tools.	No, but measure of uncertainty from short-term forecasts (reserve requirem.).	Forecast time series, or forecast error distribution for time frames of UCED, and reserve requirements.	May be needed in future.	Not needed.
Load	Hourly time series time-synchronised with wind/PV data.* At least 30 years of data for robust results.	Hourly time series based on historical data and predictions, for the full analysis period.*	5-minute to hourly time series coincident with wind/PV, for at least 1 year.* Load flexibility incorporated (flexible loads separately).	Load at nodes, snapshots relevant for wind/PV integration.	Load at nodes, high and low load snapshots. Dynamic models with capabilities and characteristics.
Load Forecasts	Not needed for traditional resource adequacy tools.	Not needed.	Forecast time series, or forecast error distribution for time frames of UCED and reserve requirements.	May be needed in future.	Not needed.
Network	Cross border capacity. Forced outage rates and mean time to repair for transmission corridors impacting.	Transmission line capacity between neighbouring areas.	Transmission line capacity between neighbouring areas and/or circuit passive parameters.	Network configuration, circuit passive and active parameters.	Network configuration, circuit parameters, control structures.
Other Power Plants	Rated capacities, forced outage rates (ideally as a time series), mean time to repair. Hydro power (dry/wet/normal year), with climate change impacts.	Investment cost, efficiency, fuel costs, emission factors. Ideally also operational characteristics from UCED.	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.

*climate change impacts are recommended to be included in wind/solar/load (and hydro) data, for studies looking more than 10 years ahead. Impact of latest wind turbine and solar PV technology with higher capacity factors also important to capture.

The recommendations are outlined as checklists for each phase of the complete study. The details for each checklist can be found in in the report chapter in question.

3.2. Power and Energy System Scenarios

The recommendations checklist of key issues for setting scenarios to study:

- When studying low amounts of wind/PV power or short-term studies, wind/PV power can be studied by adding

wind/PV generation to an existing or near future system with existing operational practices.
- For higher shares and longer-term studies, changes to the power system become increasingly necessary and beneficial – updated generation portfolio, storage assets and network infrastructure development, considering potential flexibility sources. Capacity expansion tools are recommended to construct optimised study scenarios. Additional scenarios relating to future operational practices should be studied, especially for market structures/designs, to enable flexibility.
- For wind/PV dominated power systems, modifications are so important that the system to be studied may be almost unrecognisable from the present-day system (e.g. new electrification loads, integration of inverter-based resources, reduction of synchronous machines and inertia, greater interaction with other energy sectors/carriers). Capacity expansion models should be used, while feasibility checks for operational impacts, system adequacy, and stability become much more crucial to perform. Capacity expansion tools should be improved to include:
  - Representation of demand flexibility, storage, and sector coupling, including new electrification loads, and access to options other than electrical storage as these will offer crucial new flexibility sources in the future
  - Short-term balancing in order to assess the impact of wind and solar forecast uncertainty (and nowcasting tools) on the optimal energy mix
  - Grid limitations and stability constraints, including grid expansion costs, because network capacity is very important when determining optimal wind and solar capacity in different areas
  - Operational practices reflecting future system needs and services.

4. Resource Adequacy

Resource adequacy includes estimating the security of supply, sufficient capacity and energy to meet demand, as well as the adequacy of the network to transfer the energy. A common study topic is the contribution that wind or solar energy makes towards resource adequacy estimates: capacity value.

4.1. Resource adequacy estimates

Recommendations checklist of key issues:
- Include neighbouring areas and import possibilities (including forced outage rates) during times of generation scarcity.
- Consider the impact of inter-annual resource variability as part of yearly energy reliability. Improve data, and sensitivity to capture extreme events. Current models capture correlated events, if represented in the data, which means data should span 30+ years. Forward looking data should also account for climate change impacts on resource availability and demand profiles. Temperature-correlated outages of thermal generators and common mode failures during extreme weather events should be captured.
- Include load and storage flexibility during times of high load and/or low energy resource. Chronological models are needed to assess adequacy impacts with storage resources; this is especially important for higher wind and solar shares.
- At higher shares of wind and solar (and storage) when the energy deficit volume becomes more important, use multiple adequacy criteria and metrics to fully identify, understand, and communicate risk. Aggregate metrics like LOLH and LOLE for event frequency and expected unserved energy (EUE) can indicate how severe the adequacy events are on average across a certain time period. Assess tail risks with criteria options such as metrics of the underlying distribution and severity threshold as well as through scenario-based stress tests. Assess adequacy on the seasonal and/or monthly basis as well as annually.
- Future load projections should account for the difference between electrification loads and existing loads as well as climate change impacts on demand profiles.
- For wind and solar dominated systems, consider reliability targets, allowing more hours/events per year, and rolling load shedding when load (price) responsiveness is insufficient.

4.2. Capacity Value

Recommendations checklist of key issues:
- Capacity value of wind and solar are heavily system-dependent and need to be updated to reflect the changing system buildout, configuration, and operations.
- Effective load carrying capability (ELCC) calculation is the preferred method, for wind and solar separately or in aggregate:
  - For low and medium shares of wind you can convolve generator capacity and forced outage to produce the capacity outage probability table (COPT) of the power system. LOLE for each hourly demand level is calculated from the COPT, 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 seen without wind/PV power.
  - For higher shares of wind and solar it is necessary to include storage and flexible demand in the estimation, which is difficult with COPT method. Monte Carlo simulation approach with varying load, wind/PV and hydro levels and outages is therefore recommended
  - Both methods require preserving the auto- and cross correlations between wind, PV, and load, and including enough data.
- For wind and solar dominated systems, it is recommended to use integrated planning approach where resource adequacy is embedded.

4.3. Transmission Network Adequacy with Steady-State Analyses

Specific issues and recommendations regarding power flow simulations incorporating wind and solar power include:
- *Power flow cases to study*:
  - For lower wind and solar shares, the chosen snapshots should include critical situations regarding wind and solar power, such as periods with high non-synchronous

generation (wind, solar) and/or high-voltage direct current (HVDC) imports. This is in addition to peak load and low load situations, which are traditionally studied. The correlation between demand, wind, and solar production, specific to a particular system or region, must be considered. 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 multi-year analysis.
  - For higher wind and solar shares, probabilistic analysis is recommended (as already increasingly applied by system operators), allowing uncertainty and variability across a year to be captured, with the subsequent impacts on unit commitment and dispatch decisions affecting power flows.
- *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. By analysing 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. Using UCED-OPF models to analyse dynamic line rating and other grid-enhancing technologies as alternatives to grid expansion requires improved network modelling and power flow analysis.
- *Short circuit levels*: For high wind and solar shares, 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 power quality, voltage step changes after shunt switching, and the operation of line commutated HVDC converters, and can lead to mal-operation of protection systems. Screening tools should be applied to assess the grid strength across the network for an extensive range of operating conditions.
- *HVDC grids:* A true DC power flow yields precise results for HVDC grids. DC power flow must be performed when DC transmission losses are considered, or when the HVDC system contains uncontrolled mesh networks. In other cases, it is often sufficient to omit HVDC transmission details, and to just represent the inflows and outflows of a given HVDC system as simple AC power sources.

4.4. Distribution Grid Adequacy

Recommendations checklist of key issues:

- 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 wind/PV shares to access the full capabilities and flexibilities of distributed resources for the overall bulk power system. Methods that so far have only been used for analysing transmission grids will also become relevant for distribution grid analyses.
- Distribution grid reinforcement analysis: A comprehensive catalogue of grid planning measures should be considered as part of grid reinforcement analysis, i.e. grid optimisation, before grid reinforcement, before grid expansion. 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 grid losses may deliver additional information on the effects that a further increase in decentralised generation has on the local distribution system. It is essential to consider both the location and generation profile of wind/PV sources when representing distribution grids, as they both have a significant impact on 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.

5. Operational impacts

Recommendations checklist of key issues:

- Co-incident time series of wind/PV and load (for at least one year, but preferably several years), with sufficiently high temporal resolution (at least hourly, but preferably sub-hourly). The time series should capture the locational smoothing of large-scale wind/PV power, and be representative of real (correlated) wind/PV power variations. For systems with significant weather dependency from other sources, the respective time series should be time-synchronised to accurately capture, for example, the availability of hydro power, transmission (dynamic/seasonal) limits, and contributions from combined heat and power. For systems with significant hydropower, different hydrological scenarios should be considered, e.g. wet/dry years.
- Capture all relevant system characteristics and generator/load responses through operational simulations and UCED modelling.
  - At higher wind and solar shares, it is important to model the impact of short- and long-term uncertainty on UCED dispatch decisions by, for example, introducing stochastic optimisation and rolling planning. Wind/PV forecasting best practices should be applied in relation to the uncertainty associated with wind/PV power production, including the possibility of updating forecasts closer to the delivery hour.
- Model the capabilities and limitations of flexibility sources for generation (up/down ramping limits, minimum up/down times, minimum stable levels, startup and shutdown); for interconnections to neighbouring areas (preferably by explicitly modelling, in sufficient detail, the neighbouring systems); and for operational practices (which may enable or limit the accessible flexibility over different time frames).
  - For higher wind/PV shares, new potential sources of flexibility should be included (heating, cooling, electric vehicles, storage, demand response), as these become

increasingly beneficial to the system as the share of wind/solar increases.

- Model transmission system limitations as constraints within UCED.
  - For higher wind and solar shares, congestion and N-1 security can be included directly within UCED – or analyse the transmission system using other dedicated tools with 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.
- New operating reserve targets should be estimated based upon wind, solar, and load forecast uncertainty. When calculating reserve requirements, care should be taken not to double-count uncertainty impacts, particularly if stochastic optimisation is being used.
  - At higher wind/solar shares, the inclusion of dynamic reserves, faster markets, and increased market resolution is recommended.
- Assess the existing flexibility of the power system, and apply indicators (metrics) to determine whether additional flexibility options are sufficiently economically justified. Perform a cost–benefit analysis and determine the required response characteristics of existing (and new) flexibility sources to efficiently integrate the targeted level of wind/PV energy being studied.

For wind and solar dominated systems, consider appropriate modelling complexity for a given wind/PV share. Developing suitable tools or integrated data sources to cover all such aspects represents ongoing work. It is recommended to consider at least the following issues:

- *Represent grid and stability constraints in sufficient detail*: Locating grid bottlenecks through improved network modelling and power flow analyses and including power flow control or other grid enhancing technologies that aim to reduce bottlenecks and increase transfer capacity. Stability constraints, e.g. inertial floors, may be represented by system non-synchronous share limits, or more directly by inertial or rotational stored energy (MWs) limits (unless grid-forming technology is in use); frequency control can be addressed by ensuring sufficient frequency reserves and voltage stability by confirming the availability of sufficient equipment in relevant locations.
- *Use probabilistic models and risk assessment tools*: Apply deterministic and probabilistic assessment approaches for risk-based operation using new optimisation methods and advances in (parallel, high-performance) computation as well as appropriate modelling approximations.
- *Enforce high quality information for available resources and forecast uncertainty*: Sufficiently high temporal and spatial resolution should be applied to ensure that wind and solar output is accurately represented and has a sufficiently long duration dataset to cover expected and extreme weather patterns. This should be paired with a high quality representation of forecast uncertainty, which integrates weather-dependent aspects of the system across multiple decision cycles.
- *Represent other relevant energy sectors*: Heating, cooling, transport, and power-to-X will likely have a large influence on the economics and operation of wind and solar dominated systems, and have the potential to be major sources of flexibility provision. They should be modelled with sufficient detail and resolution, both for flexibility and process constraints. In thermal power generation dominated systems, fuels provide significant flexibility. As the share of variable power generation increases and thermal generation is displaced, the need for new sources of flexibility for longer timescales increases.
- *Represent energy storage and price-responsive loads within system services*: Demand response/storage can act as cost-effective sources of system services, but potentially complex constraints relating to service availability must be carefully modelled. This may require more detailed models of the distribution system, or the aggregation of distributed resources for bulk systems, while balancing the computational burden imposed.
- *Expand market options/products for flexibility trading*: Incorporate market options for netting of system/area/nodal/individual imbalances at different timescales.

6. Network Simulations for Dynamics

Recommendations checklist of key issues:

- *Selecting snapshot cases for analysis*: A wide range of stability case scenarios, including worst case scenarios and foreseen operational conditions, should be included. 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 individual cases carefully based on comprehensive production cost simulation results. An initial screening of cases can be conveniently performed using RMS modelling, but detailed EMT analysis is required for high IBR shares.
- *Wind, PV and battery energy storage system (BESS) models:* Ensure that the models used are adapted to the characteristics of inverted-based generators, and that they are suitable for studying each particular stability phenomenon.
  - Studies should recognise that wind plant/PV/BESS controls, as part of a coordinated control strategy(s), may offer system advantages, and hence this option should be investigated in detailed electromagnetic transient (EMT) studies.
  - Generic models can be used for long-term planning studies where detailed information about generation is not available, or to represent generators remote to the area of study.
  - It is important to test the model to ensure that it is correctly parameterised (verification) to represent actual “as built” plant, and to determine the accuracy of the model with respect to measurements (validation) for all components (conventional generators, PV and wind plants, and load).
- *(Dynamic) load modelling*: With increasing shares of wind and solar generation on the distribution network, and power systems becoming 'lighter' and weaker due to the displacement of conventional generation (reduced inertia and system strength), load characteristics will more

strongly influence system performance. Existing load models should be re-evaluated, including frequency and voltage sensitivities, the time varying nature of the load composition, and hence the load models themselves should be considered. Power electronic loads and their ride-through characteristics are an emerging area of research.

- *System stability:* Different systems may experience very different dynamic issues depending on the underlying correlation between wind/PV/BESS 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.
- *Frequency stability studies:*
  - Inertial constant, droop, and governor settings of all synchronous units are needed. In addition, the frequency control block models and settings of all inverter-based resources (IBRs) (if deployed for frequency control) are required.
  - It is also important to model any protective functions of IBRs or synchronous generators that may respond to the system frequency, or rate of change of frequency, exceeding certain thresholds.
  - A reduced network representation may be sufficient.
- *Voltage stability studies:*
  - At low wind/solar/BESS shares it is probably unnecessary to perform voltage stability 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 local voltages, and if they are connected at transmission level.
  - As conventional generation is displaced at higher wind and solar shares, voltage security levels may be affected in certain locations with high concentrations of wind/solar/BESS or system-wide, requiring more detailed analysis.
- *Rotor angle stability studies:* Transient stability studies:
  - 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 recognise changes in the dynamic response of the system and respect any dynamic operating criteria (e.g. frequency variation range) adopted by the local transmission system operator. The ability of generation to ride through multiple voltage dips within a certain period may also need to be addressed.
  - Wind, BESS, 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 specific grid code requirements and the priority given to active or reactive power recovery. Proper representation of the impedance connecting the plants to the grid 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 flexible AC transmission system (FACTS) devices, synchronous compensators, and/or requiring all future wind/PV/BESS plants and conventional generators to incorporate that specific capability.
- *Rotor angle stability studies:* Small-disturbance 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 stabilisers) and alter the magnitude and direction of transmission line power flows, it follows that small-disturbance stability may be impacted.
- *Resonance stability studies:* Sub-synchronous torsional interaction and sub-synchronous control interaction should be investigated as part of small-signal stability analysis, particularly in relation to doubly fed (type 3) wind turbines radially connected with series line compensation. Sub-synchronous control interaction studies may also be performed for all IBRs that may become radially connected with series compensation after a number of contingencies. A range of mitigation measures including bypass filters, FACTS devices, and auxiliary (damping) controls are available.
- *Converter-driven stability studies:* Adequate models capable of capturing the harmonic power dynamics, especially in multi-converter setups, are crucial.
- *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 modelling 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 such as voltage dip induced frequency dips.

7. Analysing and Presenting Results

Recommendations checklist of key issues:

- 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. Comparing full scenarios are recommended, instead of extracting cost differences as integration costs.
- Present the results stating share of wind/PV (as % of annual electricity demand, not just a capacity share); size and type of power system, emphasising whether any network regions have high localised wind/PV shares.
- List main assumptions and limitations arising from these (example checklists provided).

8. Conclusions

The Recommended Practices for wind/PV integration studies has been updated to Edition 3, including first recommendations for wind and solar dominated power and energy systems. The recommendations are given as checklists of key issues, for setting up the study scenarios including input data, as well as resource adequacy, operational impacts, dynamics and finally for analysing and presenting the results.

The recommendations can be used when performing a study, or as benchmarking what has, or has not, been taken into account.

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

For wind and solar dominated energy systems, traditional study methodologies and models require re-examination. Simultaneous changes of electrification and energy sector coupling (load transition) will parallel the increases in wind and solar energy. There is a need for further development of models and methods of study, but some key issues can be identified across the challenges for adequacy, operational impacts, and system stability:

- Larger areas: The entire synchronous system is relevant for stability studies, and sharing of resources for balancing and adequacy purposes will be more beneficial.
- New technologies: All tools need to be modified to enable new types of (flexible) demand and storage, while also facilitating further links through energy system integration.
- More data and detail in models: More wind/solar details need to be captured. More data will be needed to capture higher resolution and larger areas. Extended time series will be needed to ensure resilience for weather dependent events: covering extreme events and the variability of the resources. All such issues will increase the modelling computational burden.
- Model integration: Increased importance of integrated planning and operations methodologies, tools, and data. Operational and planning timescales/models need greater overlap. Flexibility needs and plant capabilities must be incorporated within adequacy methods, and stability concerns must be considered for network expansion planning and operating future grids.

Issues identified in system studies are mainly technical, but solving them also requires identification of the most economically advantageous solutions, and ensuring that the right policies are in place in sufficient time. This will be seen particularly for resource adequacy. Traditional planning, relying on peak power as backup, may yield high cost increases for wind and solar dominated systems, unless the evolution of flexibility and price responsive loads from electrification and other energy sectors are taken full advantage of. Identified operational issues will also have economic implications, such as the sharing of system balancing and reaching out to all flexibility sources. Stability issues for wind and solar dominated systems will be mostly technical in nature, but solutions may potentially be implemented through updated grid code requirements (enforcement) and/or through the creation of new system services (incentive), with some economic impacts as well.

Market design is important to study for high wind and solar shares to incentivise operational flexibility and resource adequacy with investment cost recovery in systems with high wind/PV share, and to enable the effective use of wind/PV capabilities for power system support.

As energy supply continues to transition towards renewables, and wind and solar generation become mainstream, integration studies will become general power system design studies at very high wind and solar shares. We foresee that this Recommended Practices for Integration studies will be the last update, and, future studies are seen as multi-dimensional optimisation for the power and energy system, instead of being one-dimensional wind and solar integration studies.

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