Recommendations for Wind and Solar Integration Studies

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Abstract— **A significant number of wind and solar integration studies have been conducted in recent years, and methodologies have evolved steadily. Since power system characteristics and data availability vary significantly, the results and methodologies used in these studies have varied accordingly. This article presents findings from an international collaboration under two IEA Technology Collaboration Programmes (WIND and PVPS) working towards updating Recommended Practices for Wind Integration studies to also include those for solar photovoltaics (PV). An overview of a complete wind and solar integration study is presented as a flow chart. The set-up of a study and the main assumptions can have a large impact on the results, and therefore significant attention must be paid to ensure that these choices conform to international best practices. The main steps in the simulations are presented with recommendations on methodologies for assessing impacts on reserve requirements, on other generation and balancing, capacity value, and increases in transmission capacity.**

Keywords-grid integration, reserve requirements, capacity credit, load flow, system stability, unit commitment, wind power, solar energy

I. INTRODUCTION

Large-scale exploitation of wind and solar power can be limited by our lack of knowledge about integration impacts. For example lack of understanding of impacts lead operators and regulators to be more conservative and impose arbitrary limits, or policy makers conservative about targets for renewable energy. This is why it is important that commonly accepted methodologies are applied to these issues. Dozens of studies, complete and on-going, have been performed for wind integration, and more recent ones also include solar energy. Due to different data and models available, and also due to power system differences, the results and methodologies used vary [1]. The studies typically simulate a future power system with high shares of wind and solar, and evaluate the impacts on the grid and the resultant operational impacts on power generation [2].

IEA WIND R&D Task 25 on "Design and Operation of Power Systems with Large Amounts of Wind Power" published the first edition of Recommended Practices for Wind Integration studies in 2013 (available in (http://www.ieawind.org/task_25.html) [3]. The purpose of the recommendations report is to provide research institutes, consultants and system operators with the best available information regarding wind/solar integration studies: the various components a study may consist of depending on the system characteristics and objectives of the study as well as appropriate methodologies to use for each component. The recommendations are currently being updated, as a collaboration between IEA WIND Task 25 and PVPS Task 14. The update will include issues related to solar integration, as well as updates to the methodologies, to reflect how integration study methodologies have evolved and new experiences of real wind and solar integration have emerged.

Recommendations for integration studies will depend on the wind and solar power share studied, as defined by the energy from wind and solar resources as a percentage of yearly electrical energy consumption (gross demand). However, what constitutes a "low" share will depend on power system characteristics: 5% may be a lot in some systems, whereas 10% could be considered low in others.

The structure of this article will follow the flow chart presented in Section III: input data, set-up and portfolio development, simulations and the data analysis are described focusing on the recommendations in each of these phases.

II. SIMILARITIES AND DIFFERENCES FOR SOLAR PV AND WIND IN INTEGRATION STUDIES

While wind and solar integration studies often share similar goals and thus many similarities, there are often many critical differences that also must be taken into account.

A. Wind and solar input data

Since the same weather processes drive wind power, solar power and load, it is key that this data is coincident to ensure the interactions and temporal correlations are captured. 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 helps to avoid erroneous ramps in power output that may arise from *ad hoc* time series creation methods.

The spatial and temporal resolution of the data should match the intended goals of the study and the resolutions utilised in the power system simulations. 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. Likewise, the temporal resolution of PV resources may need to be higher than wind due to the speed of the physical processes involved (like clouds).

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*.

B. Diurnal availability of solar resource

While wind power can potentially generate during any time of the 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.

The solar generation diurnal pattern creates clear times of additional flexibility requirements within the power system, with more system 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, such as dynamic flexibility reserve requirements.

C. Size of plants and controllability

Solar PV is often installed in smaller capacities, and 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) and possibility to control the output if needed from system operators. This often results in two categories of solar PV being considered: distributed PV, which only modifies the net load shape[1], and utility PV which the system operator can control for curtailment or reserve purposes. 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.

D. Capacity factor, capacity value and curtailments

For studies focusing on the share of energy being supplied by renewable resources it is important to consider that wind and solar systems have different capacity factors (average realised 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. Consequently, for most areas, less wind power capacity is needed than PV capacity to meet target energy shares.

The capacity value of variable renewable technologies is heavily influenced by the average availability of the resource at the time of peak system load. In summer day peaking systems with large air-conditioning loads, this is an advantage for solar PV and usually a disadvantage for wind energy since 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. Also complementarities between wind and PV make a combination of both resources having operational benefits and greater production when compared to a single technology.

However, at higher variable renewable shares the effective timing of peaks due to the impact on the net load[2] is expected to change, requiring a more robust calculation method for capacity values.

For PV the daily energy is spread only to a 5- 19 hour period (depending on season and location). Surplus generation will be seen more easily for PV than for wind, for the same annual shares of wind and solar. This can result to higher curtailment needs. Concentration of the generation to fewer hours makes also the incremental capacity value of PV to decrease at a faster rate than the incremental capacity value of wind power in most locations as total capacity increases.

III. FLOW CHART OF A COMPLETE INTEGRATION STUDY

An overview of a comprehensive integration study is given as a flow chart (Fig. 1). Not all studies include all of the flow chart components and it may not be practical or necessary for all integration studies to perform each proposed step. A full study is a complicated process especially when considering all possible iteration loops.

An integration study usually begins with a set of input data characterising wind and solar power and the underlying power system along with the share of wind and solar that is of interest (the blue boxes). The electrical footprint must be chosen, which may be an entire synchronous system or a subset thereof.

The portfolio development phase establishes the kind of system that is being studied: the current or a future system, assumed or optimised generation fleet, as well as available demand and flexibility options. An important aspect is how wind and solar power are added to the system; by replacing existing old generation or by adding additional generation to the existing system.

Integration studies usually involve investigations of transmission adequacy, operation of power plants in the system and generation adequacy during peak load situations (the green boxes).

[1] new market designs may enable participation of small-scale renewable energy to the ancillary service market via aggregators bringing more of the small scale PV to the visible/controllable side

[2] By subtracting the fluctuating generation from the demand curve, the "net" load (often referred in the literature as "residual" load) is calculated. The net load describes the load that is required to be covered by conventional and flexible power plants.

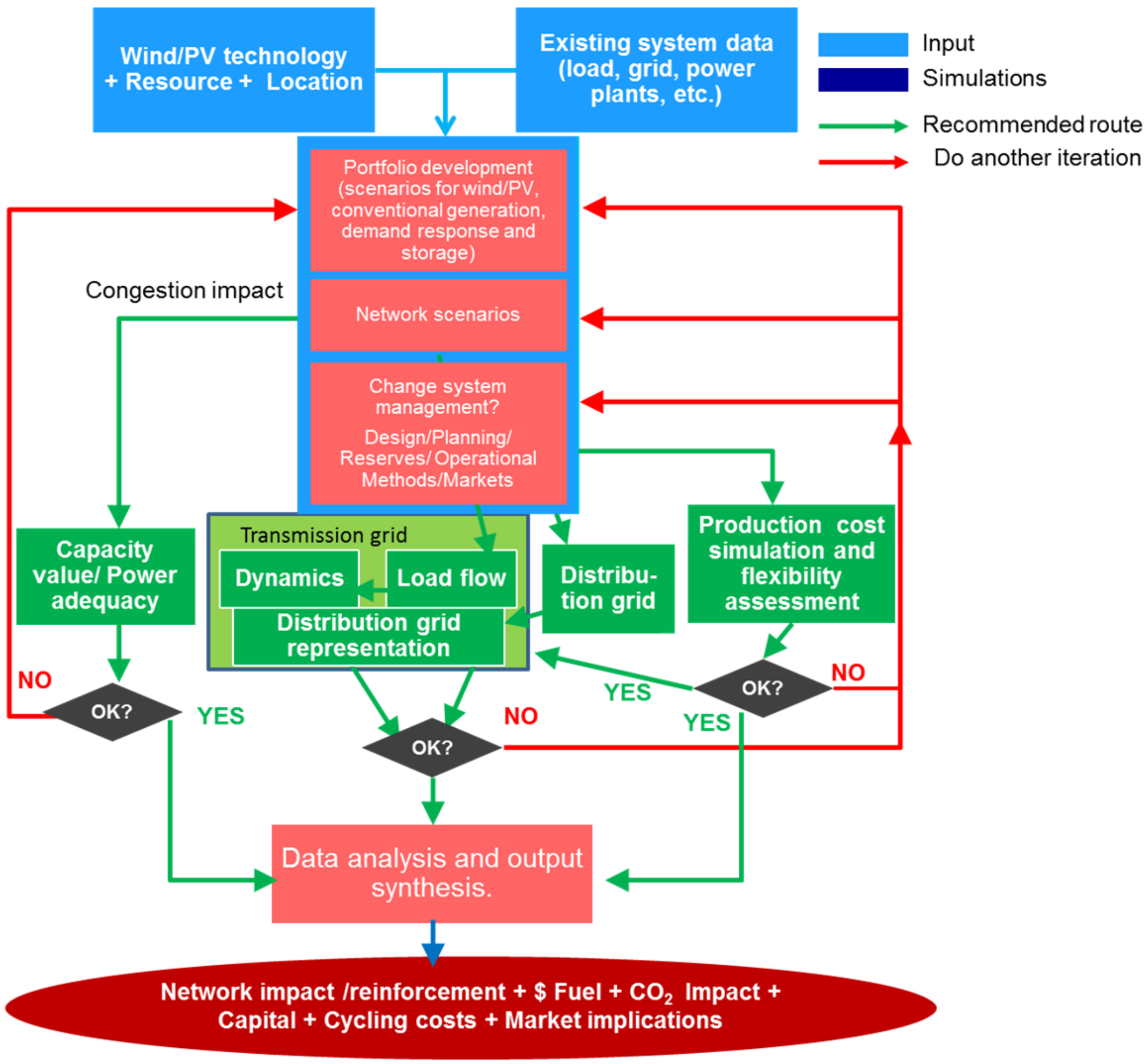

Figure 1. Integration study components. Flow chart showing a recommended route with iteration loops and possible routes when not all components are studied.

Grid simulations (load flow and dynamics) involve contingency analysis and stability studies. Dynamic simulations and flexibility assessment are necessary mainly when studying higher shares of wind and solar.

Reliability constraints from transmission or capacity adequacy or reserve margins may require iteration on the initial results to adjust the installed capacity of the remaining power plants (the portfolio), the transmission grid, and the operational practices of real-time power system management (like reserves, demand response, redispatching, special protection schemes' operation etc).

Analysing and interpreting results of wind/solar integration studies may also be challenging, as the impacts of variable resource integration and the best options to remedy impacts can be difficult to determine. Significant wind/solar shares of electricity usually necessitate conducting studies that project 10-30 years into the future. The question of how best to prepare for the possible impacts can also be extracted from simulation results, if appropriate scenarios are analysed: e.g. whether to change market structures and/or operating procedures to help ensure reliable and economic power system operation once high variable shares are realised.

IV. Input Data

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

Different volumes of data will be needed in different simulation parts (**Table 1**):

- the transmission grid is often modeled in a simplified manner, like only main interconnections between areas, when simulating dispatch,
- complete time series of wind, PV and load are replaced by snapshots in grid simulations, where the transmission grid is modeled in detail.

Recommendations regarding the input data are summarised in **Table 1**. Time-synchronised wind, PV and load data (as well as hydro power) are crucial for estimating reserve requirements and the capacity value of wind and PV generation, and simulating Unit Commitment and Economic Dispatch.

Wind and solar production time series data, that realistically represents variability, can be obtained from a combination of actual (measured) and simulated data. It is crucial to use data that represent a realistic correlation between areas and thus accounts for the smoothing effect, both spatially and at hourly and sub-hourly levels. Often up-scaling limited amount of measured data to future high installed capacity will overestimate variability. It is also important to study sufficient long-term data to calculate the probability of rare events such as fast, steep ramps of wind power – for solar the extreme ramp usually is captured with less data. Input data can be challenging to obtain especially for future systems including sites that do not have measured data, in which case back casting techniques can be used with historical data sets. When simulating future time series, a common NWP run for wind, solar, load and hydro power ensures spatial and temporal correlations between the different time series [4].

To represent the uncertainty of wind and solar generation, it is also important to model wind/solar/demand forecast updates closer to real time. Forecasting accuracy is deteriorating more quickly for longer time horizons especially for wind power compared to that of load. Wind/solar forecasting accuracy is also likely to improve in the future.

Grid simulations need to model detailed capabilities of all power plants, including wind and solar power plants. As most integration studies consider future scenarios, it is important to capture all flexibility options available.

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reserves are allocated) may be required to integrate larger amounts of wind power cost effectively.

A. Generation portfolio and transmission scenarios

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

- what kind of system is being studied – the current system or a future scenario or scenarios
- how wind and solar power are added – replacing some existing old generation or adding to an otherwise static system
- other assumptions regarding available flexibility, both technical and regulatory.

Meeting ambitious targets that have been set for wind and solar energy may require upgrades to the existing transmission infrastructure and the construction of new lines. At the same time, improved transmission network can improve the security of supply and decrease the operational costs of interconnected power systems through increased sharing of assets.

Main recommendations are:

1. when studying small amounts of wind/solar power (share in energy < 5-10 %), integration can be studied by adding wind/solar to an existing, or foreseen system without major inaccuracies
2. for larger wind/solar shares, 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).

TABLE 1. RECOMMENDATIONS FOR INPUT DATA NEEDED FOR THE INTEGRATION STUDY COMPONENTS

	Capacity value-Power adequacy	**Unit commitment and Dispatch (UCED)**	**Load Flow**	**Dynamics**
Wind and solar power	Hourly time series of at least 6-10 years, distributed wind and solar power covering the relevant areas	5 min…hourly time series of at least one year, distributed wind and solar power covering the area	Wind and solar power capacity at nodes, high and low generation and load snapshots, active and reactive power	Wind and solar power capacity at nodes, high and low generation snapshots, dynamic models of turbines, operational strategies
Wind and solar power forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	Not needed, excepting that actual line flows may differ from scheduled line flows	Not needed, excepting that actual unit outputs may differ from scheduled unit outputs
Load	Hourly time series of at least 6-10 years	5 min…hourly time series of at least one year	Load at nodes, snapshots relevant for wind integration	Load at nodes, high and low load snapshots, dynamic capabilities
Load forecasts	Not needed	Forecast time series, or forecast error distribution for time frames of UCED	Not needed	Not needed
Network	Cross border capacity, if relevant	Transmission line capacity between areas and interconnectors to neighbouring areas	Network configuration, circuit passive and active parameters	Network configuration, circuit parameters, control structures
Power plants	Rated capacities and forced outage rates	Minimum on-line capacity, start-up time, ramp rate, efficiency curve, fuel prices	Active and reactive power capabilities. System dispatch.	Dynamic models of power plants

V. PORTFOLIO DEVELOPMENT AND SYSTEM MANAGEMENT

The (future) portfolio of generation plants, transmission capacity and operational practices are all important inputs to wind and solar integration study calculations. There will also be important iterations fed back from the later phases of the integration study, as changing generation and transmission, or operational practices (including how

B. Operational methods and markets

Operational methods and markets may need to be assessed as part of the study to determine whether current approaches to operate the system and current market practice allow for reliable and cost-efficient integration of wind power. Where market structures are inhibiting access to flexibility they should be changed (such as dispatch times/faster markets, flexibilities connected to distribution grid…). Markets also need to incentivise adequate capacity.

Operational methods may change with the addition of transmission and/or more flexible generation, e.g. new transmission interconnection to neighbouring systems may enable access to more flexible generation, and at the same time reduce the overall need for flexibility in the combined system. 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 and solar forecasts, markets may be able to shorten the notification period [4]. Integration studies might investigate these issues to determine the value of such market characteristics on the ability to integrate wind and solar power [6].

Main recommendations are:

1. existing operational practice can be used as a starting point when studying small amounts of wind and solar power (share in energy < 5-10 %)
2. for higher wind and solar shares, additional scenarios or operating practices should be studied. Assess market structures/design to enable operational flexibility, including capacity markets.

C. Reserve allocation – estimating changes due to wind and solar PV

The impact that wind and solar energy have on procuring operating reserves is an on-going area of research, taking the uncertainty into account while aiming for both reserve adequacy and economic provision [7]. System operators procure reserves to balance load and generation, and to respond to outages. 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. Reserve allocation considers reserves responding across multiple timescales: a simple approach distinguishes reserve operating automatically (in seconds) and activated manually when needed (from minutes to a few hours).

The computation of reserve requirements requires estimates of the uncertainty and variability of demand, wind/solar generation and other generation sources. For wind/solar power, the forecast horizon is a crucial assumption because the uncertainty at shorter time scales will reduce more significantly than that for demand. This assumption is related to the operational practices of the power system and/or electricity markets.

A common approach is to compare the uncertainty and variability of the system (combined load and all generation), before and after the addition of wind/solar generation. Adding wind/solar generation implies allocating additional reserves to maintain a desired reliability level.

Several methods can be used to calculate the impact of wind/solar generation on operating reserves, but generally a set of recommended steps include:

1. The level of risk of insufficient reserve of a certain type must be identified. For example, one might choose to cover 95% of the variations in net load (load minus wind/solar power output).
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, (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.
3. Simple statistical methods can be used to combine the variability and uncertainty from load, wind, solar and other 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. Wind and solar -related reserves should not be static. The variability and forecast uncertainties depend on meteorological conditions and vary over time. This means that using constant reserve levels will lead to varying risk levels, or that maintaining a constant reliability or risk level will require varying reserves. It has also been found that wind power variability is highest in the mid-output range, and dynamic reserve methods have been developed that build upon this information [8].

It should be noted that there is a link between the availability of and need for reserves, since wind/solar generation, when available, can better be used for down regulation (decrease power output) than for up regulation (increase power output) and at high wind/solar levels other power plants operate at a reduced level with ability for up regulation.

VI. Capacity value

Capacity value estimation has often been performed as a separate evaluation in wind/solar integration studies. It is based on generation adequacy (often called "resource adequacy"): whether there is sufficient installed capacity to meet the electric load at some prescribed level of risk [9]. The capacity value (or credit) can be defined as the additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability [10]. Metrics used for adequacy evaluation include the loss of load expectation (LOLE), the loss of load probability (LOLP) and the effective load carrying capability (ELCC).

If the reliability (generation adequacy) target is not met by the generation mix scenario, an iteration can be applied to change the portfolio to include more generation capacity or less (or flexible) load. The capacity value calculation should recognise transmission possibilities and limits to bordering areas.

The correlation between wind/solar generation and peak load situations strongly influences the results. Hence, many years of synchronous load and wind/solar data are needed [11]. The ELCC method also requires a complete inventory of conventional generation units' capacity and forced outage rates.

The reliability level can greatly impact the capacity value of both conventional power and wind/solar power [10]. When the reliability level is low, and LOLE high, there is more value in any added capacity than for cases when the LOLE is very low. It is also important to consider the impact of import from other areas, i.e. the multi-area power system reliability [12][13]. With higher shares of wind/solar generation and a future increase of manageable load and distributed storage, the capacity value may be evaluated in a production cost simulation using Unit Commitment and Economic Dispatch (UCED), with several scenarios [14].

The recommended method for determining the capacity value is the ELCC calculation, as it determines the full net load effective load carrying capability. This can be made separately for wind and solar capacity. Also taking into account the combined power generation from wind and solar will result in higher capacity value than for one resource alone:

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 [9]. The cumulative probabilities give the LOLP for each possible available generation state.
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/solar generation.
3. Wind/solar power cannot be adequately modeled by capacity and FOR as availability is more a matter of resource availability than the plant availability. Time series for the wind and solar power output is treated as negative load and combined with the load time series, resulting in a load time series net of wind/solar generation. 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/solar generation.
5. In systems with high wind/solar share and transmission limitation between different areas where all have higher shares of wind/solar, it is important to consider the multi-area reliability [12][13].

VII. Flexibility Assessment and Production Cost Simulation

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. Typical sources of flexibility include conventional generation which can be dispatched up and down; upward and downward regulation of wind and solar power (with an associated impact on production); load shifting and load shaving that is starting to be used increasingly; and storage (with comparatively high capital costs for new installations). Transmission allows for the sharing of flexibility across interconnected regions.

Various methods have been proposed to assess the flexibility adequacy of power systems and to develop adequacy metrics with respect to their flexibility [15][16]. These methods are evolving and may become more important in systems with high shares of wind and solar power. So far, flexibility assessment is generally conducted implicitly within production cost simulations. Production cost simulations consist of simulating the hour to hour operating schedules of generating resources such that operating costs are minimised and system and operational constraints are satisfied. Unit Commitment involves determining the optimal on-off schedule of units on the system while Economic Dispatch determines the operating level of committed units (UCED). Possibilities of flexibility resources may also be captured as an increased system value of wind and solar [17].

Production cost simulation is the main study vehicle to assess the impacts of wind/solar power integration on flexibility, operating costs and emissions. It involves optimising the scheduling of load and generation resources to meet expected demand over various time frames with consideration of cost and constraints (system, physical, and operational) and expected wind/solar power. The constraints in the optimisation ensure the physical feasibility of the short-term operational plans and reliability under uncertainty. With increasing levels of wind/solar energy it is important to capture more detail and the current constrained optimisation paradigm may need to be adapted. Recommendations:

1. 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 optimisation and rolling planning method [18]. The general diurnal pattern of Solar PV is quite predictable but weather effects like cloud cover can result in some uncertainty.
2. Increased operating reserve targets should be estimated using wind, solar and load forecast uncertainty. With higher wind/solar shares, use of dynamic reserves, faster markets and increased market resolution is recommended.
3. To assess the true capacity of the system to respond to change, the limitations and constraints of the system must be accurately modeled. This includes inflexibilities of conventional plant, such as minimum generation levels, ramp rates, minimum up/down times, start times, load times, and for hydro power plants the degree of freedom to control power production considering river flow constraints. To capture these limitations, it may be necessary to use mixed integer programming (MIP). 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.
4. To accurately model the limitations of interconnections with neighbouring regions, the neighbouring system should be explicitly modelled to some degree [19]. Alternative approaches include assuming full availability of interconnectors or to assume fixed flows obtained from other studies or based on assumed market prices in neighbouring regions. These

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

5. To capture the limitations from the transmission network, it is important to consider congestion and N-1 security within UCED. To reduce the computational burden for large systems or where stochastic optimisation is used, net transfer capacity, or iterative methods can be used. In systems with very high levels of renewable generation, it may also be necessary to model additional stability constraints arising from the studies described in section IX.
6. In systems with significant amounts of hydro power it is essential to consider different hydrological scenarios (wet/dry years).
7. Study results and conclusions are particularly sensitive to the non-wind/solar case used as a basis for comparison and assumptions regarding the types of generation that wind/solar power will displace, especially if estimating integration costs. Using a scenario with equivalent wind energy but with a perfectly flat power profile may result in impacts not entirely related to wind energy [2].

VIII. Network studies: load flow

Once production cost simulations have indicated that a given wind/solar integration scenario is potentially feasible, more detailed analyses are performed, to assess if the plant portfolio and (transmission and distribution) grid are adequate 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 dynamic issues. The chosen deployment of wind generation (including different wind turbine technologies and wind distributions) and solar generation (different solar - PV and concentrated solar - technologies and residential uptake of installations) can also be evaluated against existing grid code requirements, and considering different mitigation or participation options.

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

1. Creating a number of credible load flow cases. Snapshots chosen should include critical situations regarding wind and solar power, such as high non-synchronous generation (wind, solar) and import via classical LCC HVDC periods, in addition to peak load and low load situations traditionally studied. It is noted that there will be some form of correlation between demand, wind and solar production, specific to a particular system or region. An evaluation of the snapshot's statistical relevance would be beneficial, perhaps as part of a multi-year analysis, as an input to the cost-effectiveness of implementing corrective actions.
2. Deterministic steady-state security analysis. In compliance with N and N-1 security criteria, load flow analyses are performed to identify transmission network bottlenecks (congestion), and to assess the system's ability to control the voltage profile.
3. Network loading (congestion) assessment. Network branch loadings should be determined for wind / solar generation and load combinations, over a year, both for normal and contingency situations. Bottlenecks can be identified in a probabilistic manner, so that by analysing the overload risk and the aggregated severity index, planners can decide whether bottlenecks are 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.
4. Time-series load 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 & 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.
5. Short circuit levels. At high wind & solar shares of production 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 some 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.
6. Protection systems. Increased generation 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 [20].

IX. Transmission system dynamic stability analyses

Stability studies become increasingly important once the instantaneous share of wind and solar energy keeps exceeding 50% in a synchronous system. Dynamic studies are required in order to assess that the system is robust against a variety of system events and disturbances. These studies typically include transient analyses and dynamic rotor angle stability studies.

Low shares of wind and PV generation are unlikely to have a significant impact on system stability. More than 50 % instant shares may be anticipated in smaller synchronous systems already when approaching a 20 % annual share.

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

- transient stability (i.e. angle stability): ability to maintain generator synchronism when subjected to a severe transient disturbance
- small-signal (oscillatory) stability: ability to maintain synchronism when subjected to a small disturbance
- frequency stability: ability to maintain system frequency following a major imbalance between generation and load
- voltage stability: ability to maintain an acceptable voltage profile after being subjected to a disturbance.

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 modelling complexity will depend on the nature of the analysis, balanced against the size of the system and computational power available.

- For large scale system studies it is standard practice to utilise generic wind turbine dynamic models developed by the WECC and IEC [21], [22] and which are intended for short-term (10 -30 s) analyses. These capture the minimum performance required in most grid codes for the four basic types of wind turbines. 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 [23].
- 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 of how to determine aggregate distribution-connected PV model parameters has not yet been formed, but analytical methods involving both transmission- and distribution-level modelling haves been proposed [24][25]. Development of adequate dynamic distribution models with distributed wind, PV, storage systems etc. is more and more required. Here especially the complexity and diversity of the distribution level is a major challenge.
- Increasingly, wind power plants are being located offshore, and connected via HVDC transmission to the existing onshore grid. Modelling 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.
- Finally, although (dynamic) load modelling has generally received limited attention, the increased shares of wind and solar generation on the distribution network, and 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 [26].

Recommendations for configuring the dynamic simulations include:

1. A wide range of wind & solar share and demand levels (recognising the correlation between inputs) shall be included to best understand the dynamic system limits.
2. Frequency stability studies require the inertia, droop and governor settings of all units to both simulate individual unit responses and the combined system response to major faults or contingencies, and to assess changes in frequency regulation capacity. A reduced network representation may be sufficient.
3. Small-signal stability studies require automatic voltage regulator (AVR) including power system stabilizer (PSS) settings for synchronous generation. 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.

The stability issues of concern for a particular system will depend on system size, wind & solar distribution relative to the load and other generation, along with the unit commitment and network configuration. They are likely to be first seen during night-time or seasonal low demand periods when the instantaneous share of production from wind may be high, or during the shoulder seasons for solar PV when demand levels are comparatively low, even in cases when the annual energy contribution is not very high. Wind & solar curtailments are one solution to avoid system stability issues, so the primary objective of any analysis is to identify (future) areas of concern, before considering the benefits of applying soft measures, e.g. modified controller settings, implementing power flow control schemes, introducing flexibility-based ancillary services, or hard measures, e.g. network reinforcement, constructing / retro-fitting flexible generation plant, which may require iterative feedback to the generation portfolio and transmission scenarios (Section V), and production cost modelling (Section VII) stages. Recommendations for analysis and study options include:

- For frequency response, the fraction of generation participating in governor control is a good metric for expected performance [27]. The maneuverable capacity of such generation is also important, with resources that provide significant incremental power 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.
- Reduced inertia at times of high non-synchronous penetration will alter the system response for both faults and contingencies, which can be particularly important for smaller power systems or those connected by HVDC links. Modern wind turbines can provide an emulated inertial response, but it is not always available and changes with turbine operating point [28]. Fast acting load response, or power injection from energy storages are also beneficial.
- To mitigate transient stability problems, 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.
- Wind & solar generation can provide system support during voltage dips, although the level of support provided is network sensitive, capability may also vary depending on the priority given to active or reactive power recovery, and proper representation of the impedance connecting the wind farms is crucial within simulation studies. However, a recent blackout in south Australia suggests that there may be manufacturer imposed limits on the number of voltage dips that can be rode through in a certain period.
- Voltage stability has in many cases been found to be unaffected or enhanced by the presence of wind turbines, particularly if their reactive power control

capabilities to manage voltage are deployed [29], and if the turbines are connected at transmission level. At higher shares of wind and solar, as conventional generation is displaced, voltage security levels may be affected.

- Wind & 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 signal stability may be impacted [30].
- Sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI) should be investigated as part of small-signal stability analysis, particularly noted for doubly fed (type 3) wind turbines. A range of mitigation measures including bypass filters, FACTS devices, auxiliary (damping) controls are available. [31].
- System stability studies should recognise that wind turbine controls, as part of a coordinated control strategy(s), may offer system advantages [32]. It should also be noted that VSC-HVDC can, to a certain extent, also be used for system stabilisation [33].
- Network faults and/or loss of a major infeed can result in a large frequency deviation and the common-mode tripping of local wind & solar generation. Consequently, the operation of associated protection systems may play a crucial role in determining system outcomes, requiring sophisticated modelling methods [34]. Delayed active power recovery from grid code compliant generation following a widely seen network fault may lead to a common-mode power reduction and frequency stability issues - voltage dip induced frequency dips [35][36].

A. Considering HVDC transmission infrastructure

The presence of HVDC transmission infrastructure, especially future HVDC grids, can make network simulations and calculations challenging. The HVDC transmission infrastructure itself is rather straightforward to represent, compared to the AC transmission infrastructure, due to the nature of direct current: Only 2 instead of 3 conductor, no reactive power/current and constant values in steady state (unlike the 50 Hz AC fluctuations).

The calculation is therefore convenient: a true DC power flow, which yields precise results and not an approximation (as when AC networks are calculated with simplified DC power flow). However, challenges are caused not by the DC network itself, but by the AC-DC HVDC converter stations that interface the HVDC transmission infrastructures with the AC grid. The behaviour of these converters is determined mostly by their controllers and not by the physical properties of the devices (such as a synchronous machine). Synchronous machines often have similar technical parameters, since they are constructed in a similar manner. Differences can stem from various technologies for the excitation system, or a different number of pole pairs. However, HVDC converter station controllers can behave very differently (constant power control, constant voltage control, droop control, etc.), and their control mode can easily be changed and very rapidly (e.g. voltage margin control).

For fast transients in the millisecond range, the DC system dynamics also need to be considered, implying detailed models with reduced simulation time steps [37]. When considering dynamic analysis, HVDC converter stations usually behave in a highly non-linear manner for transient stability simulations. While for small-signal assessment, linearisation 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.

There are three common converter types in use, which all show different fault responses: 1) VSC (ABB HVDC Light generation 1-3) 2. LCC (or CCC), known as classical HVDC and 3) MMC. When simulating a network with HVDC transmission assets, making assumptions is unavoidable. The control details of existing equipment are usually proprietary, making it challenging to implement the real behaviour. Most studies, however, consider future scenarios, when future HVDC transmission assets should be considered, although technology details and controllers cannot be foreseen. Consequently, simulation conclusions (e.g. the system is stable) should always be treated with some scepticism, and variation should be applied to the input assumptions (e.g. is stability maintained if the HVDC stations operate under a different control mode?) [38].

X. Distribution Grid Studies: Load Flow and Variability Analysis

Particularly for smaller systems, interconnection at the distribution system is often favorable 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 created by such scenarios. Distribution-connected wind and PV in aggregate need to be included in analysis as outlined for Transmission system in this section, but further impacts to the distribution system which they connect are also likely to occur.

For distribution-level grid studies the two most prominent concerns are maintaining an acceptable voltage profile along the distribution circuit and both maintaining acceptable levels of power quality and ensuring existing utility voltage regulation equipment will continue to operate as designed and intended. To alleviate these concerns load flow and variability analysis studies are typically completed. Many other types of studies including: protection, unintentional islanding, reverse power flow, equipment overload, and dynamic generator response, are also completed when necessary.

Not including the distribution-level studies in an integration study risks inaccurate scenario selection as the technical ease or difficulty of distribution-level integration of wind and/or PV may significantly reduce or increase expected costs of integration. Another important aspect is including more detail of distribution networks and distribution network connected resources for transmission system studies, as mentioned in Section IX.

A. Load Flow Studies

Distribution-level load flow studies are typically scenario based. 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 [39]. 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.

B. Variability analysis

Variability analysis of a distribution circuits operation over a relatively long period of time (e.g. a year) is often 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 is starting to be used in Europe to better manage distribution-system-level variability due to integrated PV. Such equipment is effective at regulating voltage but can also have shortened lifetimes or require more maintenance if operated more often as may occur when connecting wind and PV. Variability analysis study methods vary from relatively simple classification of expected analysis from wind/solar resource data [40] to full-scale quasi-static time-series (QSTS) simulations of a distribution circuit over an entire year [41].

XI. Analysing and Interpreting the Results

When analysing simulation results, it should be noted that it is possible to iterate back to earlier stages in the flowchart of Fig. 1, including rethinking of initial assumptions. This may be desired if the impact of wind and solar proves difficult or costly to manage. This underlines the importance of the main set-up and the portfolio chosen, as well as more flexible operational practices.

Integration cost is a concept that covers the additional costs that are required in the power system to meet customer quality requirements (voltage, frequency) at an acceptable reliability level (and do not include the costs for installing new power plants and connecting them to the grid). However, correctly extracting such costs is difficult and should be undertaken with care [42]. It is challenging to draw out the system cost for a single form of generation because system services exist for all loads and generators. In the case of transmission costs induced by wind or solar power (except in the case of a radial connection), the allocation is challenging because additional transmission provides increased reliability.

Although it is difficult to extract the cost of variability and uncertainty from integration studies, it is relatively straightforward to assess the total operational cost for non-wind/solar and high shares of wind and solar cases, and these operational costs can be compared. Here the challenges lie in how to choose the non-wind/solar case to be able to extract the wind and solar induced costs only.

The impact of wind and solar power plants on transmission losses and grid bottleneck situations can be significant in some cases and therefore may need to be assessed. If transmission adequacy needs associated with wind or solar power integration are of concern for only a small fraction of the year, network investments can potentially be postponed using for example topological modification, curtailment/re-dispatch, dynamic line ratings to increase transmission line capacity and coordinated control using FACTS devices and/or VSC-HVDC and demand response.

An increased level of reserves caused by wind and solar may be procured by conventional generators that are used to supply energy in the non-wind/solar case, and are used to supply less energy and more reserve in the wind/solar case. During times when wind and solar power output increases, other generating units must back down, allowing them to provide up-reserve if needed.

A comparison of results for different methods is challenging, making it important to present results using metrics that other studies have used, stating also the wind and solar shares in energy and the size of the power system, as well as all relevant assumptions and limitations of the methodology chosen [3]. Results of integration studies should be discussed in detail to keep in mind the assumptions made and the weaknesses of the estimates.

XII. Conclusions

Wind integration studies have become wind and solar integration studies. They have been maturing continuously as the state of the art advances, with each study generally building on previous ones. A complete wind and solar integration study includes a main set-up with portfolio selection and system management inputs, simulations of capacity value, production cost simulation and transmission network and finally analysing the data.

There are important iteration cycles from the simulation parts to portfolio set-up 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 the simulation parts include how to take wind and solar power into account, as well as how to model the system to accurately capture wind and solar impacts.

Results of integration studies should be discussed in detail to keep in mind the assumptions made and the robustness of the estimates. When studying differences between wind and solar and no-wind/solar cases choosing the no-wind/solar case is challenging – making sure that the differences are due to wind and solar addition only.

Integration study methodologies continue to evolve and new experiences of real integration will emerge. Recommendations will be updated as part of continuing international collaboration under IEA Technology Collaboration Programmes.

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