Recommended Practices for wind/solar integration studies

IEA Wind TCP Task 25: Design and Operation of Energy Systems with Large amounts of Variable generation in collaboration with IEA PVPS TCP Task 14

WINTER 2025 ETSAP MEETING

24th Nov, 2025

Hannele Holttinen, OA Task 25/63, Finland

Contents

IEA Wind TCP

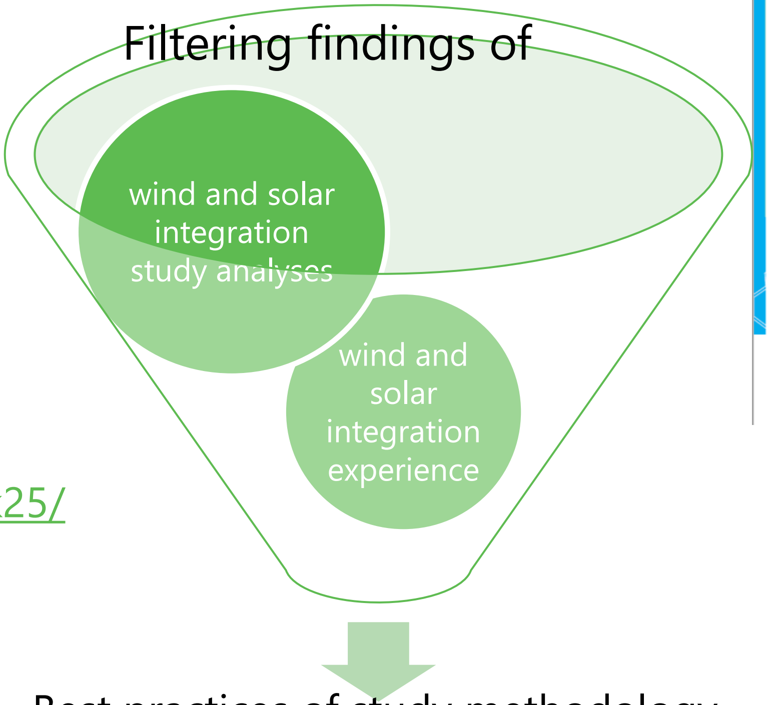
- IEA Wind Recommended practices for wind/PV integration studies
  - energy system coupling – storage buffers
  - Recommendations for capacity expansion tools and assessing adequacy*
  - Summary
- Net zero studies – review
  - Challenges – Methodologies to recommend – future joint work with our TCPs?

- (*Extra slides: Recommendations also for input data; studying operational impacts and impacts on power system stability, as well as analysing and presenting results).

IEA Wind Task 25/6 in a nutshell

- Started in 2006, 15-18 countries participate

https://iea-wind.org/task25/



Best practices of study methodology.
Evolving solutions and mitigation measures

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Recommended Practices – what, why and for whom

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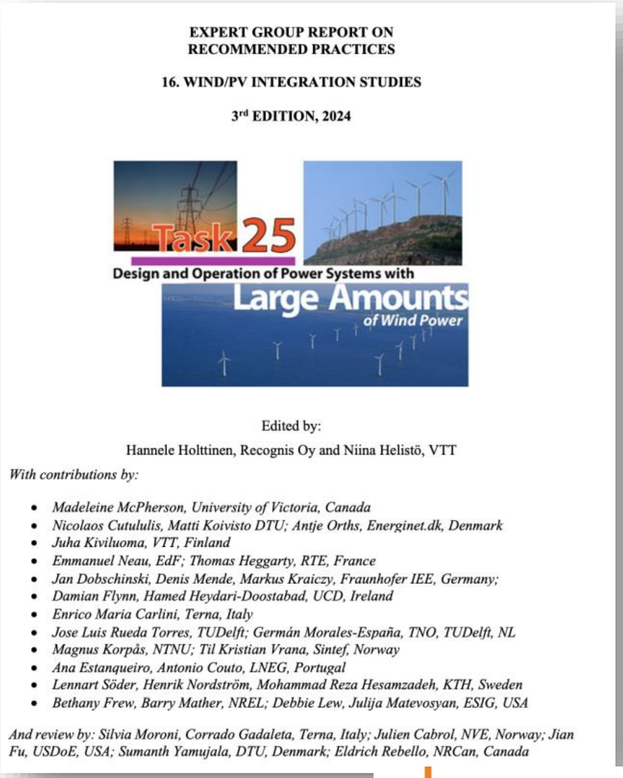
- to provide research institutes, consultants, and system operators with the best available information on how to perform an integration study.
- can also be used as a benchmark for any existing grid integration study - what is taken into account and what is not
- Recommendations on how to perform studies: methodologies, assumptions, and inputs needed for system impact studies
  - No results (refer to our summary report for results)


EXPERT GROUP REPORT ON
RECOMMENDED PRACTICES

16. WIND/PV INTEGRATION STUDIES

3rd EDITION, 2024

Task 25
Design and Operation of Power Systems with
Large Amounts
of Wind Power

Edited by:
Hannele Holttinen, Recognis Oy and Niina Helistö, VTT

With contributions by:

- *Madeleine McPherson, University of Victoria, Canada*
- *Nicolaos Cutululis, Matti Koivisto DTU; Antje Orths, Energinet.dk, Denmark*
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Edition 3 of RP16

Published end 2024

IEA Wind TCP

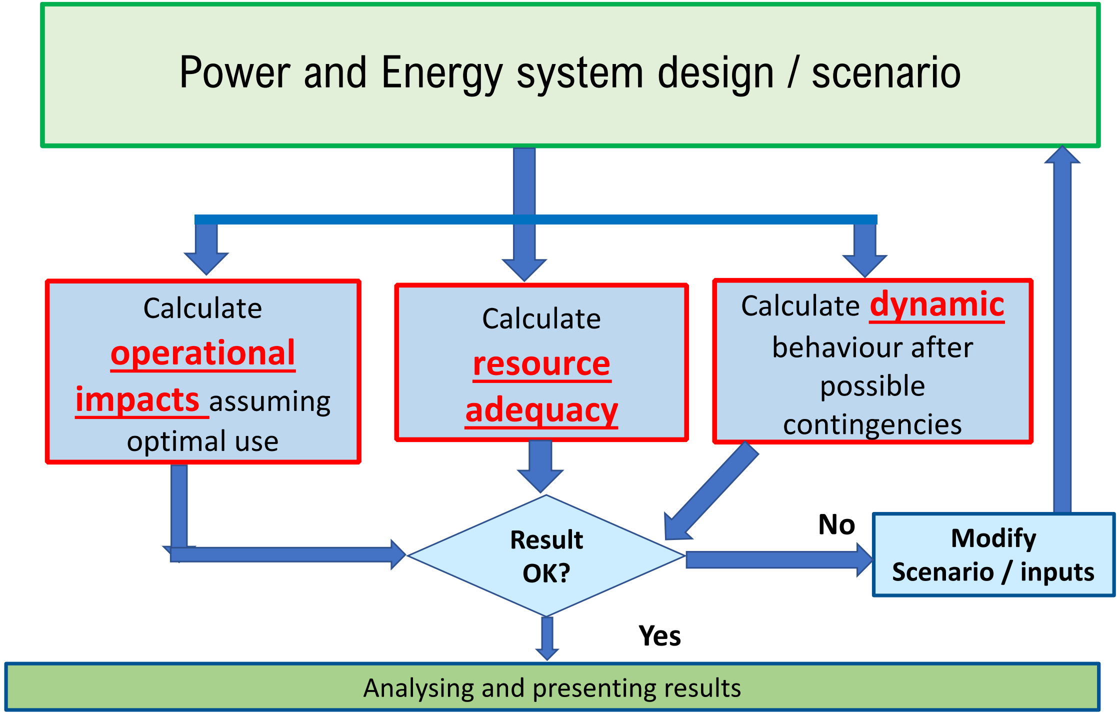
Builds on Edition 2 from year 2018 that added solar, and distributed grid (PVPS TCP)

→a new flow chart

→Previous edition for small, and medium shares of wind/solar

→ Added a third layer, for wind/solar dominated systems

→a lot of revisions in text



Energy system coupling – storage buffers

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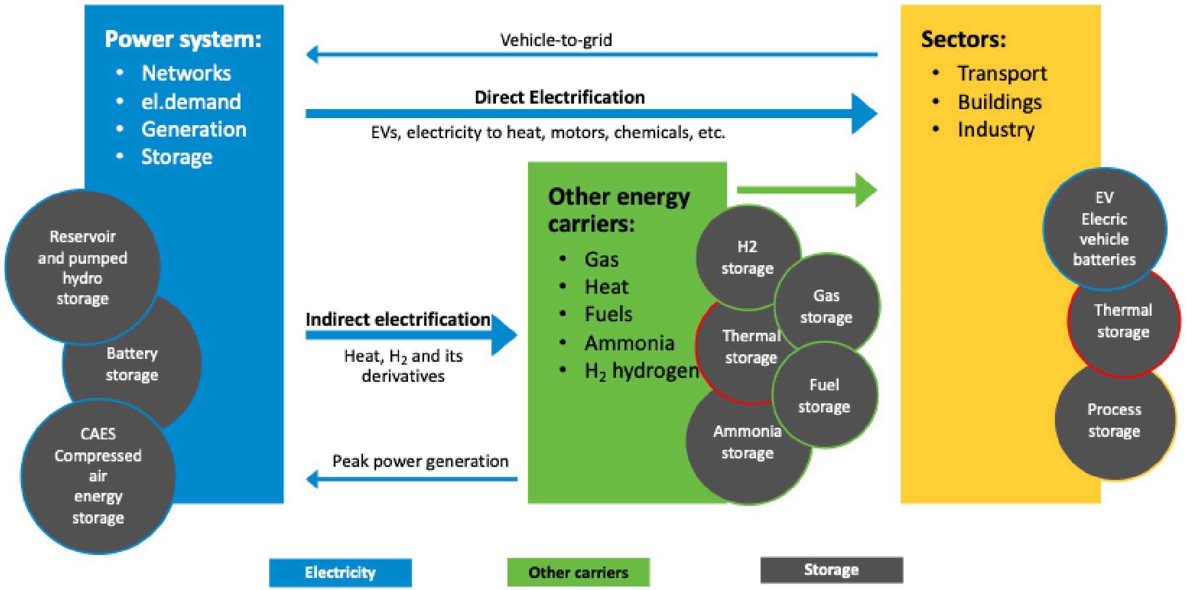
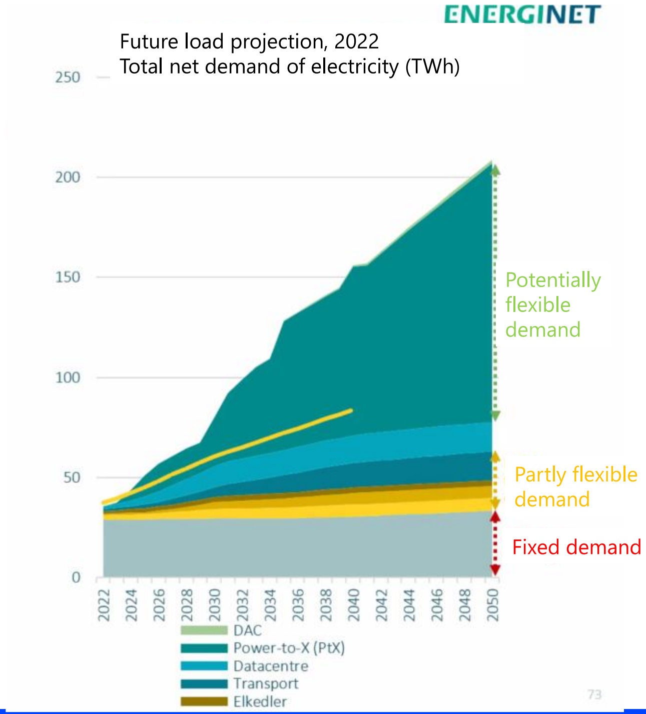
Future load scenarios include new types of demand response from power2X, and storage components like thermal storage coupled to power2heat





Future scenarios should be optimised

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Wind/PV dominated systems

- Changes will be so important that the system to study becomes completely different: new electrification loads, integration of IBR, reduction of synchronous machines, interaction with other energy sectors/carriers
- Capacity expansion models for optimised scenarios – and all the feasibility checks become crucial
  - Emission targets can be included
  - Also transmission lines btw areas can be optimised
  - Energy system coupling taken into account
  - Flexibility inputs important – including operational practices

Recommendations for Capacity Expansion Tools

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Demand and storage

- Improve representation of demand flexibility, energy storage and sector coupling including access to other than electrical storage

Short-term balancing

- Include short-term balancing in order to see the impact of forecast uncertainty on the optimal capacity mix

Grid

- grid limitations and stability constraints, including grid expansion costs: network capacity is very important when determining optimal wind and solar capacity in different areas

Markets

- operational practices reflecting future system needs and services

Model tools to assess future energy systems

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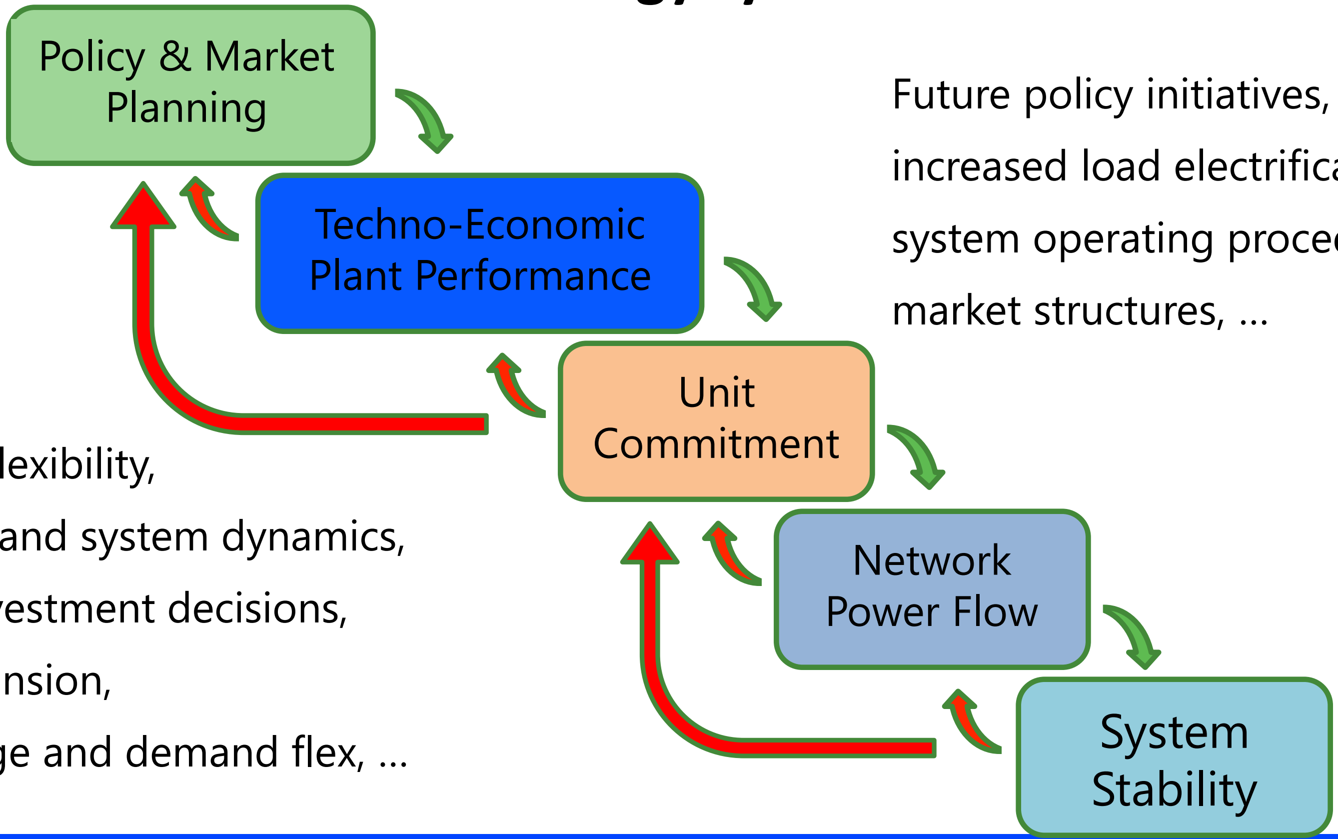
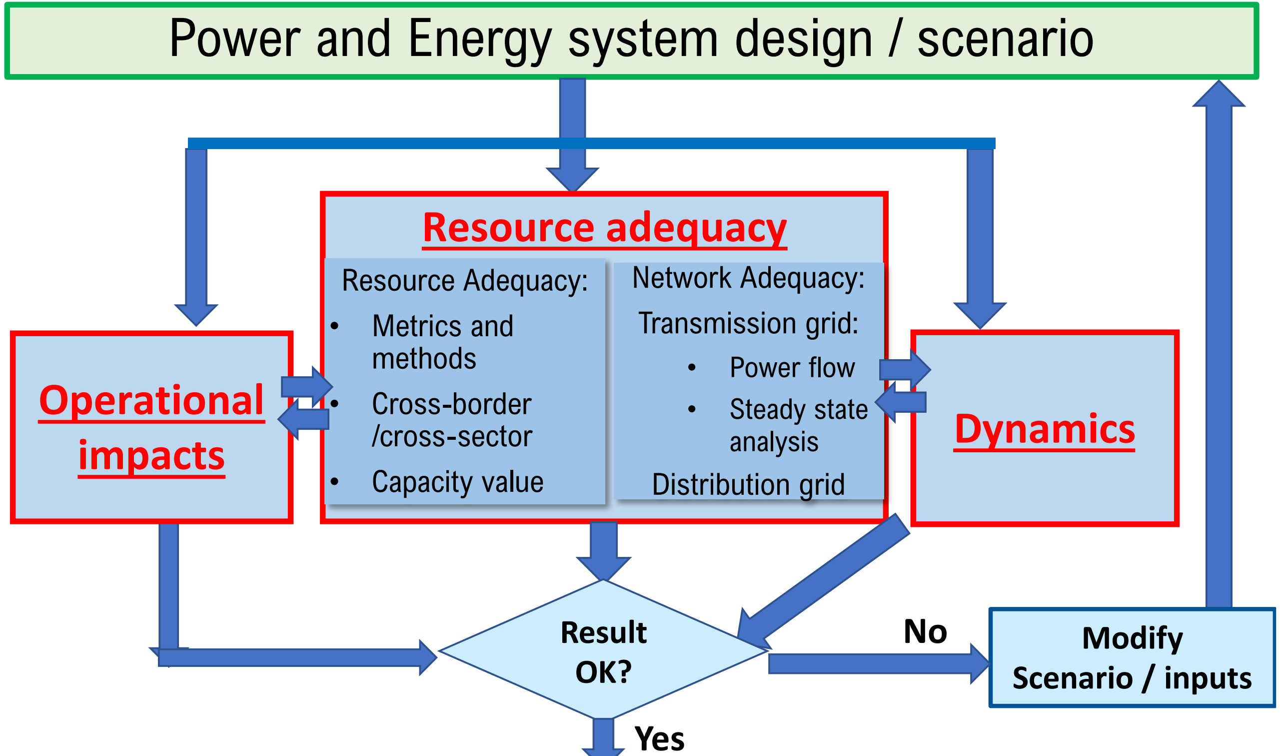


Future policy initiatives,
increased load electrification,
system operating procedures,
market structures, …

Operational flexibility,
plant cycling and system dynamics,
impact on investment decisions,
network expansion,
energy storage and demand flex, …

Adequacy impacts (Chapter 4) Resource Adequacy



Results: LOLE, LOLP, EENS, capacity value of wind/solar. Efficient use of existing network or requirements for new network investments

Ensuring resource adequacy of scenario - recommendations

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Neighbouring areas

- Import possibilities (including forced outage rates) during times of generation scarcity
- Recent model developments using Monte Carlo

Inter-annual resource variability

- Enough data to capture extreme events (30+ years)
- Energy adequacy
- Climate change impacts on resource availability and demand profiles

Chronological models

- To include load and storage flexibility at times of scarcity of energy
- Difference of electrification loads to existing loads, and climate change impacts on demand profiles

New adequacy metrics

- Use LOLH (Loss-of-load Hours) and LOLE (Expectation), and EUE (unserved energy), assess tail risks
- Reliability target - which critical loads must be served

Summary: Recommended Practices for wind/PV integration studies

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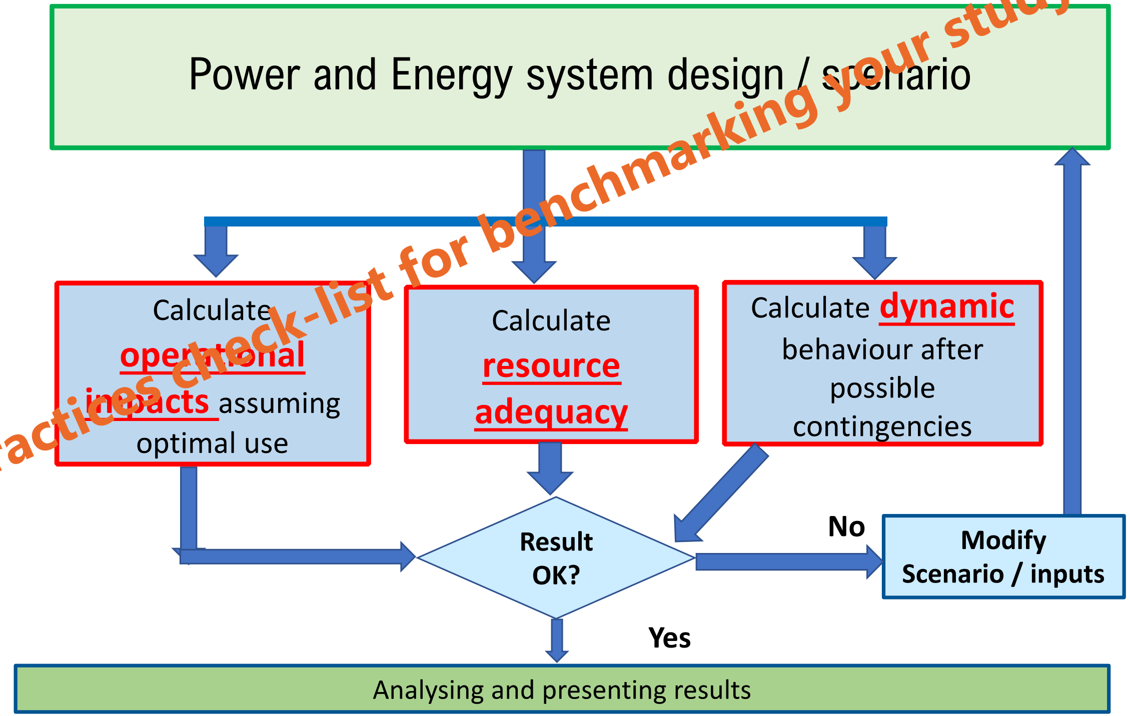
- Most studies analyse part of the impacts – goals and approaches differ
- Built on many inputs and assumptions that should be transparent
- A complete study with links between phases becomes more important at higher shares of wind/PV



Use the recommended practices check-list for benchmarking your study!

Future work - evolution of methodologies

integration studies are becoming general system studies for energy transition

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Larger areas
- the entire synchronous system for stability
- sharing of resources for balancing and adequacy purposes

Complexity
- increasing computational burden capturing detail
- higher resolution for larger areas, with extended time series for weather dependent events

Demand and storage
- new types of (flexible) demand and storage,
- further links through energy system coupling

Model integration
- integrated planning: methods, tools and data, overlap btw operational models
- Flexibility needs and plant capabilities within adequacy, and stability concerns for network expansion and operational tools

Cost vs. risk
- reliability interface needs revisiting
- evolution of flexibility and price responsive loads

Task 25

- Design and operation of power systems with large amounts of wind power

Main authors of Recommended Practices in red

- 17 countries + Wind Europe participate

Country	Institution
Canada	UVic (M. McPherson); Uni Laval (A. Rabiee); NRCan (Eldrich Rebello)
China	SGERI (Wang Yaohua, Liu Jun)
Denmark	DTU (Nicolaos Cutululis, Matti Koivisto); Energinet.dk (Antje Orths)
Finland (OA)	Recognis (Hannele Holttinen); VTT (Niina Helistö, Juha Kiviluoma)
France	EdF R&D (E. Neau); TSO RTE (T Heggarty); Mines (G. Kariniotakis)
Germany	Fraunhofer IEE (J. Dobschinski); FfE (S. von Roon); TSO Amprion (P. Tran)
Ireland	UCD (Damian Flynn); Energy Reform (J. Dillon); SEAI (J. McCann)
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Norway	NTNU (Magnus Korpås); SINTEF (John Olav Tande); NVE (Julien Cabrol)
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Sweden	KTH (Lennart Söder, Mikael Amelin); SvK (Robert Eriksson)
UK	Imperial College (Goran Strbac); ORECatapult (D Nwobu)
USA	NREL (B.Frew); ESIG (D.Lew, J.Matevosyan); EPRI (A.Tuohy); DoE (J. Fu)
Wind Europe	European Wind Energy Association (Vidushi Dembi)

Net zero studies article and working paper

SEAI_WorkingPaper_Literature_Review_of_Energy_System_Studies_with_Focus_on_NetZero_Emissions.pdf

UNIVERSITÉ LAVAL

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1. Near Zero electricity systems studies
   - BERKELEY LAB
   - **USA, Japan, South Korea, China, India,…**
2. Net Zero and clean electricity system studies
   - NREL, ofgem, iea
3. Net Zero energy system studies
   - Princeton University; The University of Melbourne, The University of Queensland Australia, Princeton University, nous; Canada Energy Regulator; Rte
4. International Net Zero economy
   - iea; Evolved Energy Research; EDF

Power system technical conditions for net zero carbon studies

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(1) maintaining **system strength and stability** as conventional synchronous machines are replaced by inverter-based resources which requires solutions such as synchronous condensers and grid-forming converters;

(2) ensuring **system adequacy** through the development of flexibility resources, including dispatchable peaking units, large-scale storage, demand-side management, and expanded interconnections;

(3) adapting **operational reserves** and forecasting methods to address the increased uncertainty and decentralized nature of VRE, particularly distributed solar PV; and

(4) upgrading the **transmission and distribution grid infrastructure** to accommodate a more dispersed and variable generation mix.

RTE "Energy Pathways to 2050: Key Results," Paris, France, October 2021.

Challenges and Recommendations

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- Energy System Integration Power system-focused studies: interactions between key sectors beyond the power system at a sufficient level of detail. Broad energy system modelling studies: individual sectors in sufficient detail to produce optimised technology investments.
- System Flexibility Needs should influence investment decisions - include chronological modelling at least hourly
- Long-Term Storage: co-optimise investment and operations; sufficient temporal resolution to capture short-term flexibility value, and long-term chronology to capture seasonal and security of supply value.
- Network network detail and investment pathways with the opportunities for co-optimisation across sectors
- Security of Supply and Resource Adequacy considerations of adequacy across multiple weather years
- System Stability and Services consideration of the services required by the system in the technology investment planning

SEAI_WorkingPaper_Literature_Review_of_Energy_System_Studies_with_Focus_on_NetZero_Emissions.pdf

seai SUSTAINABLE ENERGY AUTHORITY OF IRELAND

All models have limits -problem size and level of detail, while obtaining solutions within reasonable timeframes

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- consider the broader energy system holistically, in both planning and operational time frames, to identify least cost pathways and synergies.
  - Solution: Interconnected Models and Workflows, iterative model linking. Optimal selection of representative periods and consideration of long-term chronology. Decomposition (like Benders)
  - Challenge: incorporating high-resolution modelling in the optimisation process and capturing key uncertainties
- Modelling these larger systems presents a number of challenges, and best practices are evolving at pace. Could we formulate Recommended Practices for these studies, joint work with ETSAP and Wind Task 25/63?

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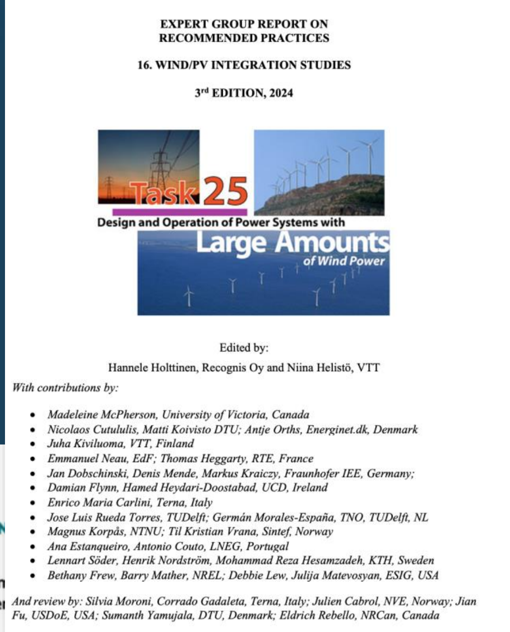
Report published at IEA Wind TCP web site https://iea-wind.org/iea-publications/ and as IEA PVPS TCP report

WISO and ESIG presentations on Recommended Practices in Practice

- Context: IEA TCP WIND Task 25 Recommended practices for wind/solar integration studies
- Context: Chalmers study on Electrification in Sweden
- Compare practice to recommendations
- Suggestions to facilitate high quality integration studies

- paper/presentation available at ieawind.org/Task25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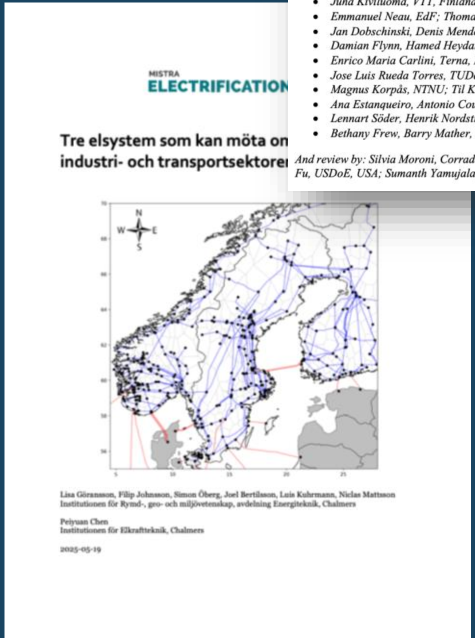

Tre elsystem som kan möta on...
industri- och transportsektore...

Lisa Göransson, Filip Johnsson, Simon Öberg, Joel Bertilsson, Luis Kuhrmann, Niclas Mattsson
Institutionen för Rymd-, geo- och miljövetenskap, avdelning Energiteknik, Chalmers

Peiyuan Chen
Institutionen för Elkraftteknik, Chalmers

2025-05-19

Extra slides – Recommendations for input data, power flow simulations, operational impacts and stability

Input data: Recommendations for simulation tools

	Resource Adequacy/ Capacity Value	Capacity Expansion Model	UCED and 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.

An important note added:

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- Climate change impact to wind/solar/hydro and load data
  - There are caveats in current climate model data, care not to increase uncertainty when data cannot be validated
  - Run simulations also with best possible data from historical measurements/weather model simulations
- Technology impact (increased capacity factors) to wind and solar data

Capacity value of wind/solar - recommendations

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- Capacity value is heavily system-dependent
  - need to be updated to reflect the changing system buildout, configuration, and operations
- ELCC method recommended to assess the capacity value of a certain asset
  - How much increase in load will bring same reliability/LOLP in the system when adding wind or solar (or combined): Effective Load Carrying Capability ELCC.
  - Monte Carlo methods for higher shares of wind and solar where storage and flexibility demand important to capture (not COPT as previously recommended)
- Synchronous wind/PV/load data. Number of years for robust results: 30+
- For wind and solar dominated systems
  - capacity value for separate technologies will no longer be meaningful - integrated planning approach where resource adequacy is embedded recommended

Transmission planning - adequacy of the network

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- Recommendations report addresses network adequacy by steady-state feasibility checks (Ch 4) and stability checks (Ch 6) while transmission scenarios form part of power system scenarios (Ch 3)
  - ❖ Transmission system operators’ transmission planning process not in RP report
  - ❖ Many more RES scenarios required than previously evaluated (probabilistic weighting)
- If steady-state and/or dynamic feasibility checks are failed then transmission network enhancement options must be investigated
  - ❖ Reinforce transmission lines, or invest in grid enhancing technologies
  - ❖ Combined power flow analyses and UCED required to fairly analyse dynamic line rating, and other grid-enhancing technologies, as an alternative to network upgrades

Transmission adequacy steady state checks - recommendations

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Power flow cases to study

- Snapshots of critical situations, considering correlation btw load
- Statical relevance of cases
- Higher shares of wind/PV: capturing variability over the year with dispatch decisions

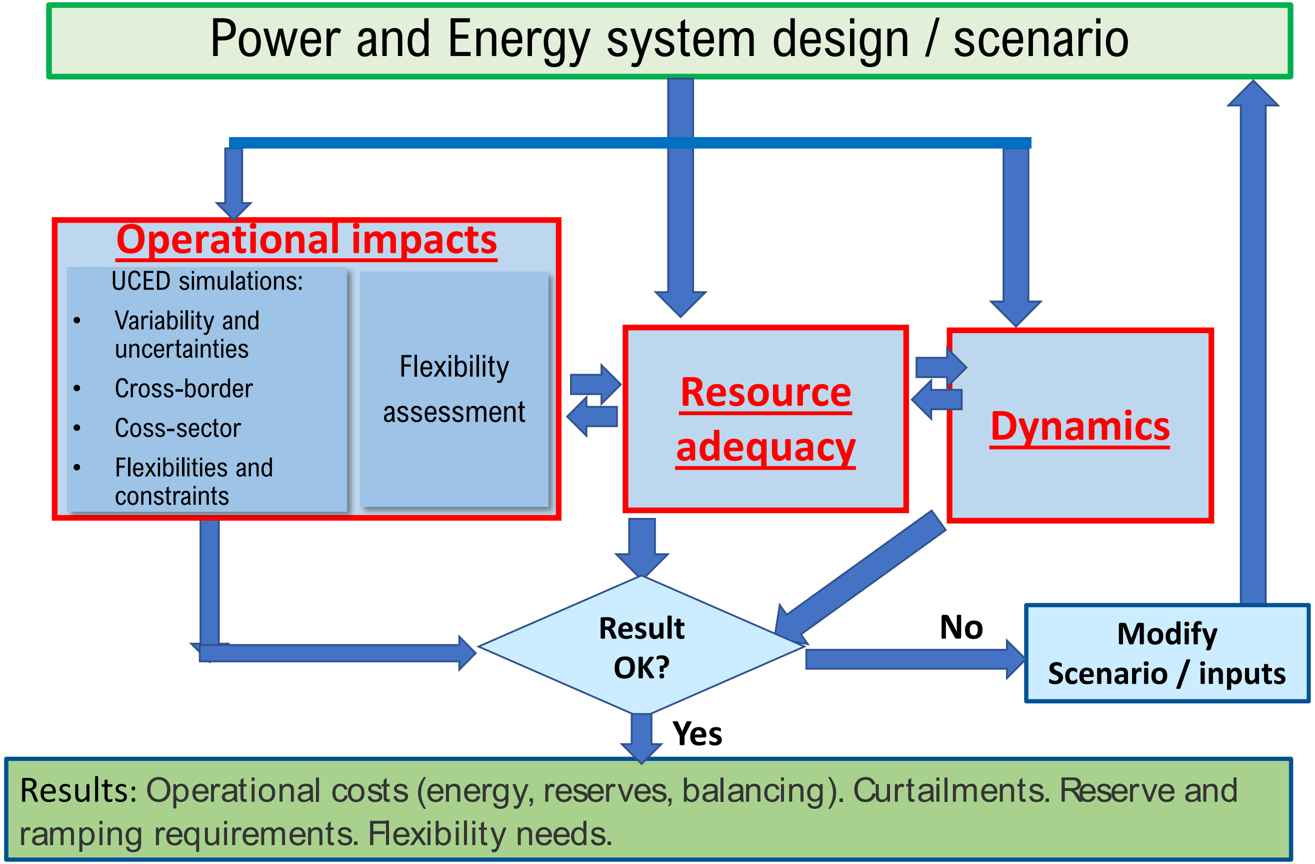
Deterministic steady-state security

- Power flow analyses to identify bottlenecks and ability to maintain voltage profile
- Improved network modelling to analyse grid enhancing technologies ability to mitigate

Short circuit levels (weak grids)

- Assess locations where short circuit levels reduced
- Screening tools for grid strength across the network

Operational impacts (Chapter 5)



Ensuring that the studied scenario is operable

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- Ensuring sufficient flexibility to cope with demand variability and uncertainty, renewable generation variability and uncertainty, profitability and unforeseen (dimensioning) events
- Simulated with Unit Commitment and Economic Dispatch (UCED) tools, to evaluate the impact of wind/PV on the operation of other power plants
- Iteration loops /sensitivies often needed; results sensitive to base case selection (non-wind/PV case of comparison)
- Input data: at least one year of at least hourly wind/PV data – synchronous with load (and hydro) and capturing smoothing impact and forecast accuracy

Managing variability and uncertainty – reserves and scheduling

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- Closer to real-time gate closure
- Stochastic or robust scheduling
- Increased scheduling frequency
- Multi-period unit scheduling
- Shorter scheduling intervals

Figure 5.3. Management of operational flexibility through scheduling strategy or reserve product design (Source: EPRI, 2019).

Cause	Type	Resolve in Scheduling	Approximating Reserve Examples
Variability	Between Intervals		Flexible ramping reserve
Variability	Within Interval		Frequency control reserves – regulation
Uncertainty	Between Intervals		Flexible ramping reserve
Uncertainty	Within Interval		Frequency control reserves – contingency
Uncertainty	Before First Interval		None currently proposed

Operational impacts - recommendations

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Time series of wind/PV, load

- At least hourly resolution
- Synchronised with other weather dependent sources
- Paired with forecast uncertainty
- Hydro: wet/dry years

Base case scenario

- Results from wind/PV scenarios from comparisons are sensitive to choice of base case
- Capacity expansion models for consistent scenarios

Operational simulations

- UCED models
- At higher shares model impact of uncertainty on dispatch decisions – stochastic optimisation, rolling planning

UCED recommendations

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Capabilities and limits of flexibility

- Ramping, min up/down times, min levels
- Neighbouring systems
- Operational practices: market options
- Other relevant energy sectors: heating, cooling, transport, P2X

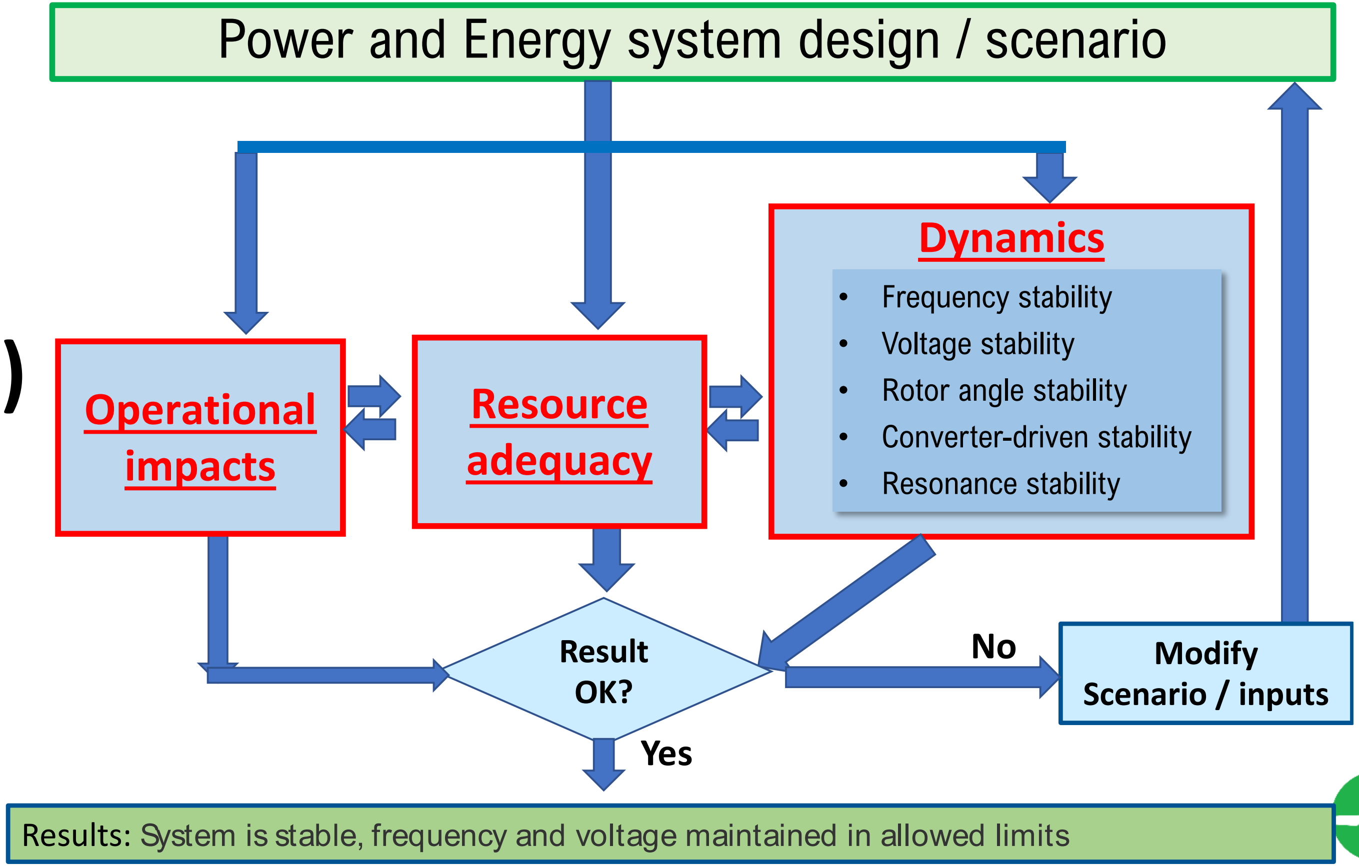
Grid constraints

- From separate analysis
- Grid enhancing technologies for grid bottlenecks
- Stability constraints links to contingency reserves; locational reactive/inertia etc capability

Operating reserves

- Based on wind, solar, load forecast uncertainty
- Take care not to double count
- At higher shares include dynamic reserves, faster markets

Dynamics (Chapter 6)



What to study: depending on particular system concerns

- Determine if the grid is sufficiently robust to sustain disturbances (temporary and and dimensioning contingencies), and capable of recovering satisfactorily
- Evaluate dynamic impacts from newly connecting generation or load to the power system – and deployment against grid code requirements
- Investigate impact of different distributed generation locational distributions
- Assess transmission limits when these are set by a combination of transient stability, small-signal stability and/or voltage stability concerns.
- Assess impact of sub-synchronous interactions as part of small signal stability analysis
- Determine optimal measures to avoid generation curtailment due to dynamic constraints.

Dynamics - recommendations

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Selecting cases (snapshots)

- Worst case scenarios
- Foreseen operational conditions
- Based on UCED
- Initial screening with RMS modelling

Wind/PV/BESS/Load models

- suitable for studying each particular stability phenomena
- ensure correctly parametrized (validation)
- consider variety of control options that modern power electronics offer, adapted to the particular systems studied.

Stability cases relevant for the system

- Frequency / voltage stability
- Rotor angle stability (transient and small-signal)
- Resonance and converter stability
- Common mode failures

Simulation tools

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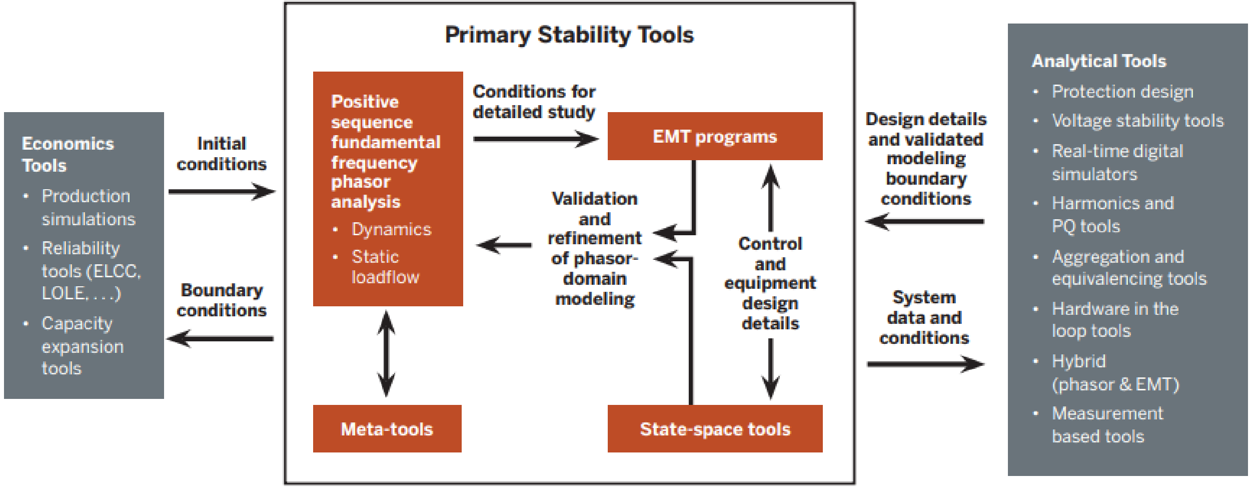
- Need to move to more detailed electro-magnetic transient simulations (EMT)
- Models for components needed for evolving wind/solar technology, and new loads

FIGURE 27
Stability Simulation Environment



Source: HickoryLedge.

Recommendations: Frequency and Voltage stability

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- *Frequency stability studies:*
  - The inertia, droop and governor settings of all synchronous units, and frequency control block models and settings of all IBRs providing frequency control are needed
  - Model any protective functions in IBRs or synchronous generators that may respond to 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: stability is likely to be unaffected or even enhanced by the presence of wind turbines/PV panels if the reactive power control capabilities deployed
  - At higher shares of wind and solar: voltage stability may be affected in certain locations with high concentration of wind/solar/BESS or system-wide as conventional generation is displaced.

Recommendations: Rotor angle stability

- *Transient stability studies:*
  - Include effect of protection devices for both network and converter-interfaced generating equipment. Protection relay settings should not conflict with the local TSO interconnection requirements. 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. Proper representation of the impedance connecting the plants is crucial.
  - To mitigate, fast acting reactive power response devices during and following disturbances can be applied (e.g. FACTS, synchronous compensators, and/or requiring generation/storage for that specific capability)
- *Small-disturbance stability studies:*
  - Small-disturbance stability may be impacted if conventional generation (and associated power system stabilizers) are displaced and magnitude and direction of transmission line power flows are altered.

Recommendations – Resonance and Converter

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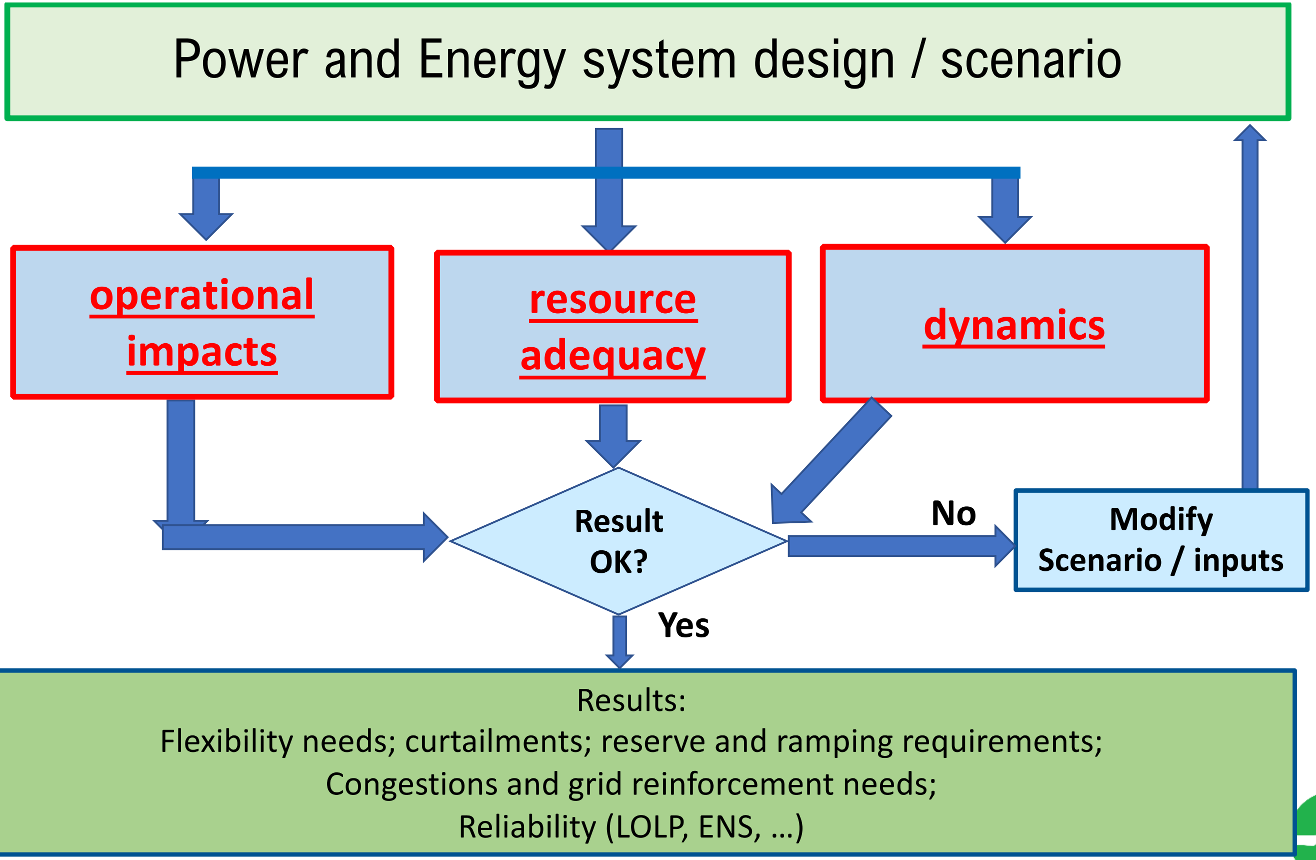
- *Resonance stability studies:*

- Sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI) should be investigated as part of small-signal stability analysis, particularly in relation to doubly fed (type 3) wind turbines radially connected with series line compensation. SSCI 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 and should be considered

- *Converter-driven stability studies:*

- Adequate models able of capturing the harmonic power dynamics, especially in multi-converter setups are crucial.

Analysing results (Chapter 7)



Analysing and presenting the results

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- Iterations provide significant insights
  - importance of the main setup and scenario chosen as the basis for the results, as will have crucial impacts on the results.
- Comparisons to base case selected may impact results.
  - Integration cost contradictory issue – so far no accurate methods found to extract system cost for a single technology
- For easier comparison with other studies, present
  - Share of wind/PV, size of the power system; potential curtailments
  - all relevant assumptions and limitations of the methodology chosen: interconnections, flexibilities,

Use the recommended practices check-list for benchmarking your study!