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Recommended Practices in Practice

How to include wind and solar in system studies

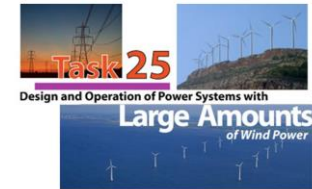
Lisa Göransson, Peiyuan Chen, Chalmers University of Technology

Hannele Holttinen, Recognis, OA IEA Wind Task25/63

Damian Flynn, University College Dublin, WP lead Stability IEA Wind Task 25/63

Compare Practice to Recommendations

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



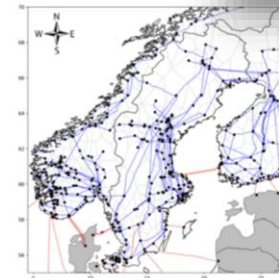
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Tre elsystem som kan möta on industri- och transportsektore



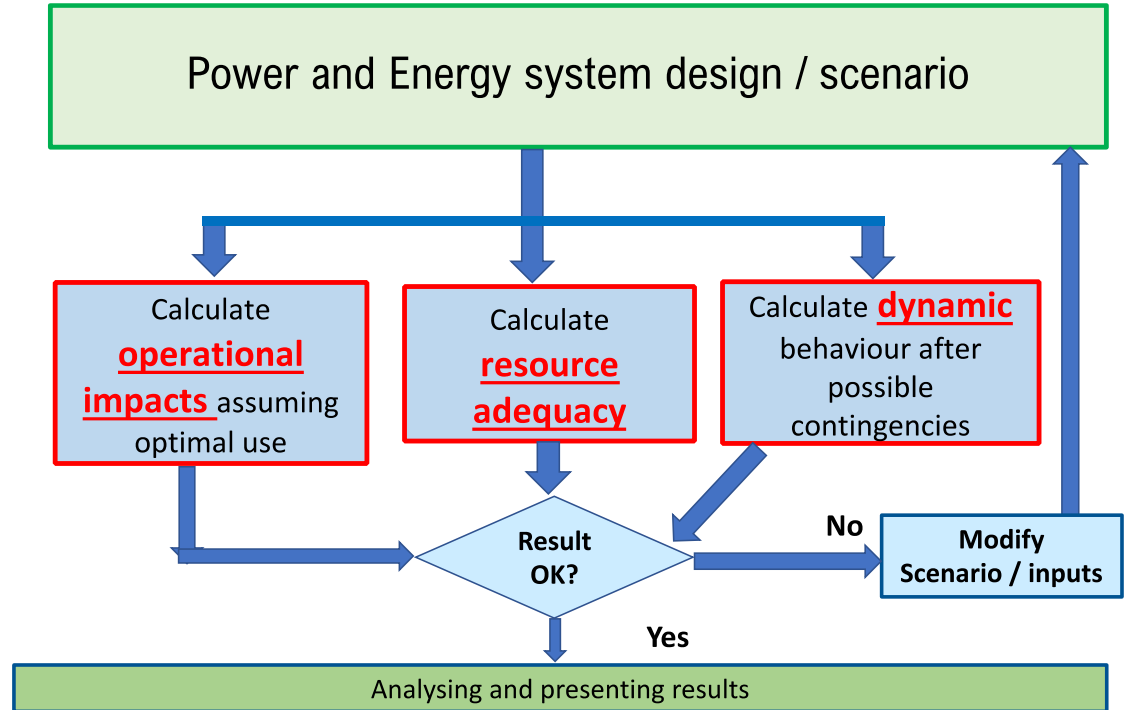
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2025-05-19

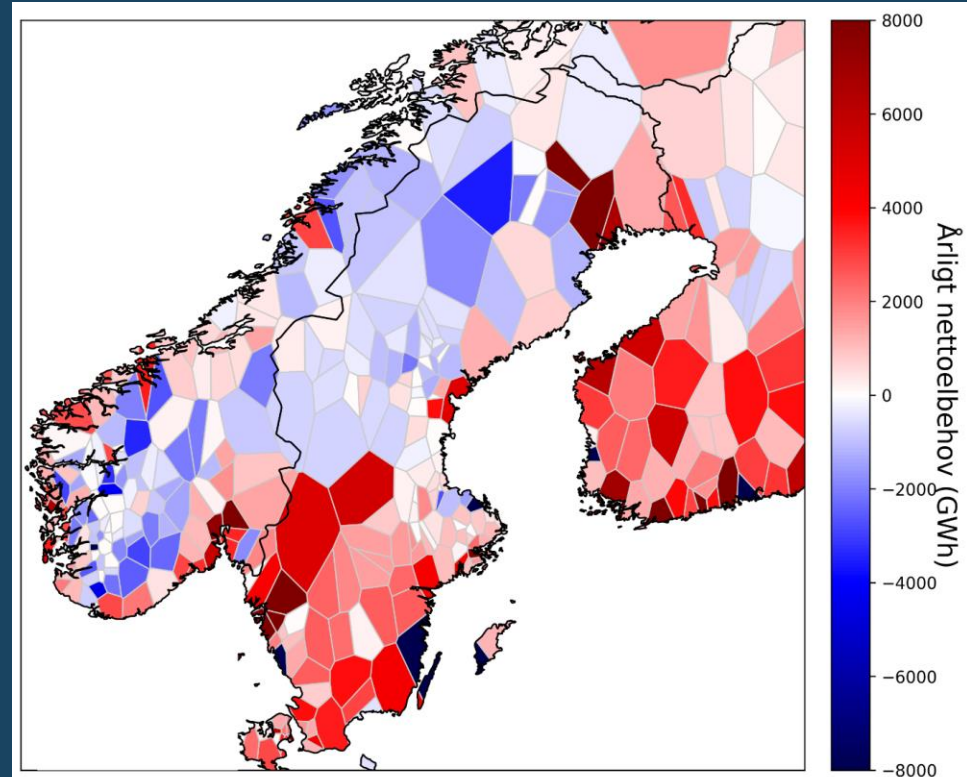
Context: Recommended Practices RP

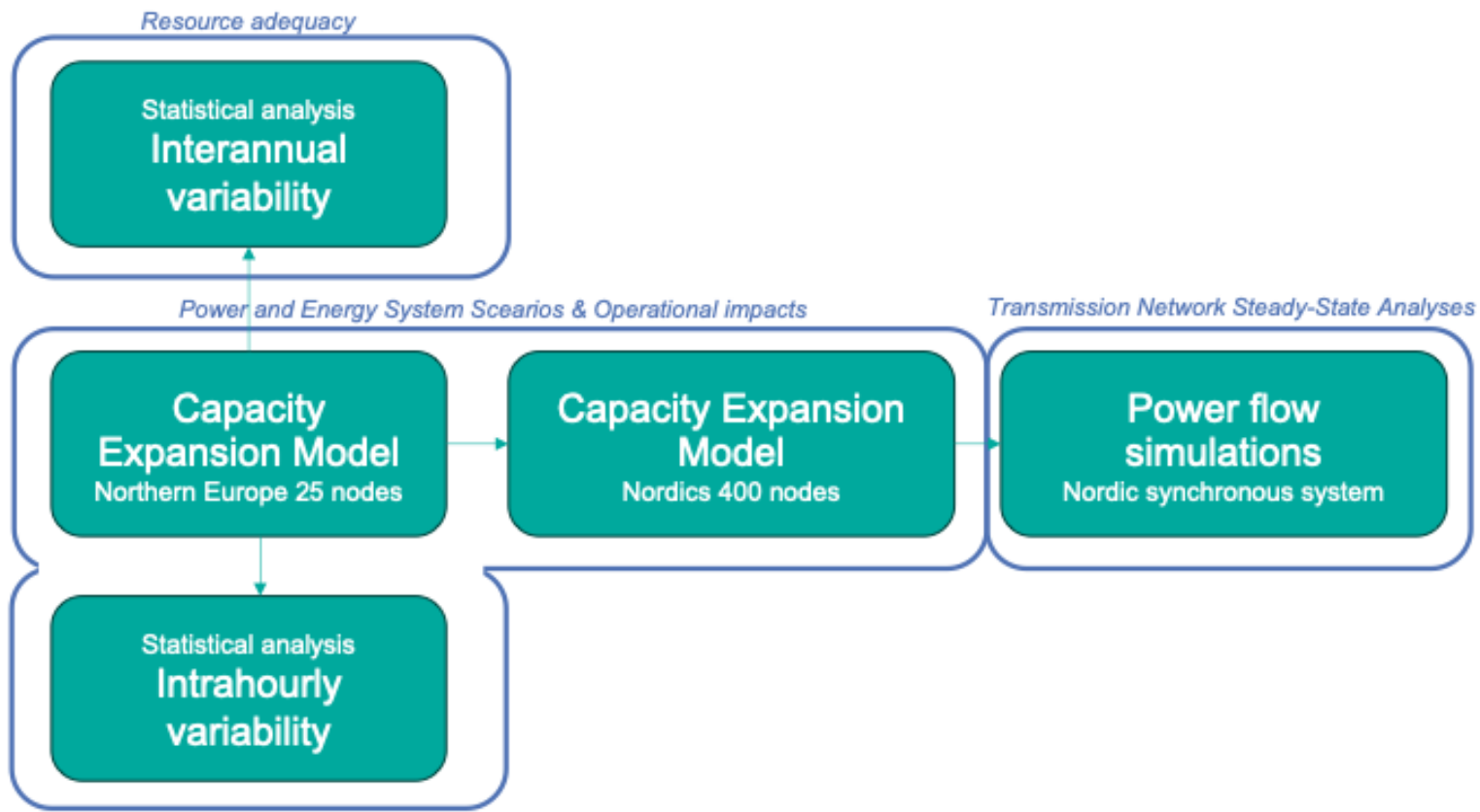
- To provide researchers, consultants, and system operators with the best available information on how to best perform an integration study
- Can also be used as a benchmark for any existing grid integration study - what is taken into account and what is not
- Recommendations on how to perform studies: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



Context: Chalmers Study on Electrification in Sweden

- Climate neutral by 2045
- Increased electricity demand from energy-intensive industry
- How can the electricity/hydrogen/heat demand be met at lowest cost for society?
- What is the full cost of a wind dominated energy system?





Aspects to Address in a Wind Integration Study

- Power and energy system scenarios
- Resource adequacy estimates
- Capacity value
- Transmission network steady-state analyses
- Distribution grid studies
- Operational impacts
- Network and dynamic simulations
- Analysing and presenting results



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Power & Energy System Scenarios

Swedish study in short:

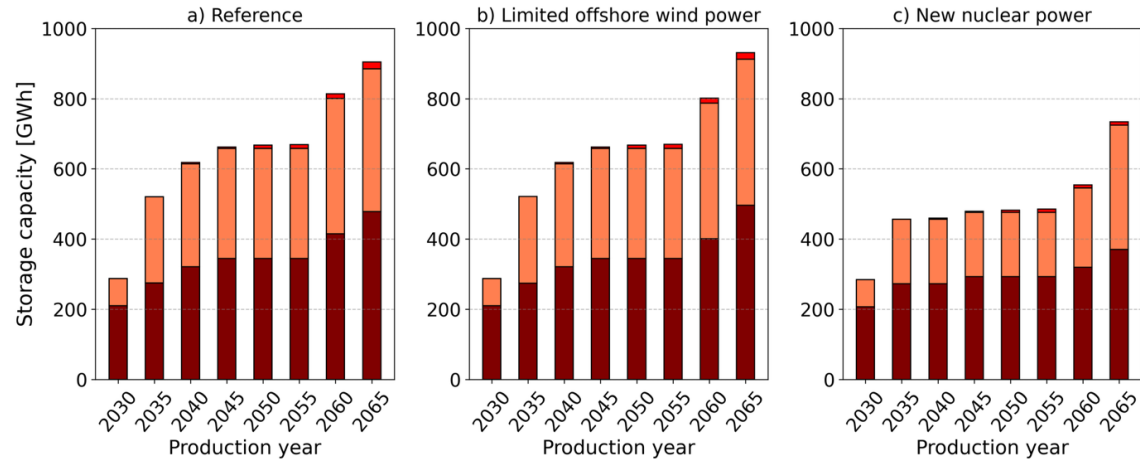
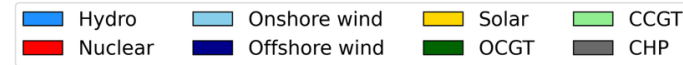
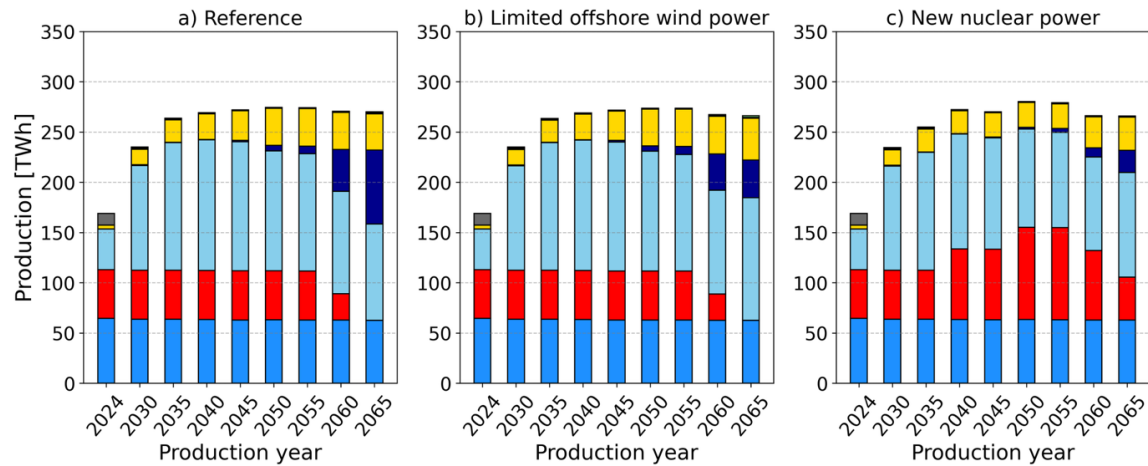
2 capacity expansion models, both with high temporal resolution, one with long time span and one with high geographical resolution

2 cases compared – with and without new nuclear power

Assumption: Variability and grid limitations have large impact on total system composition

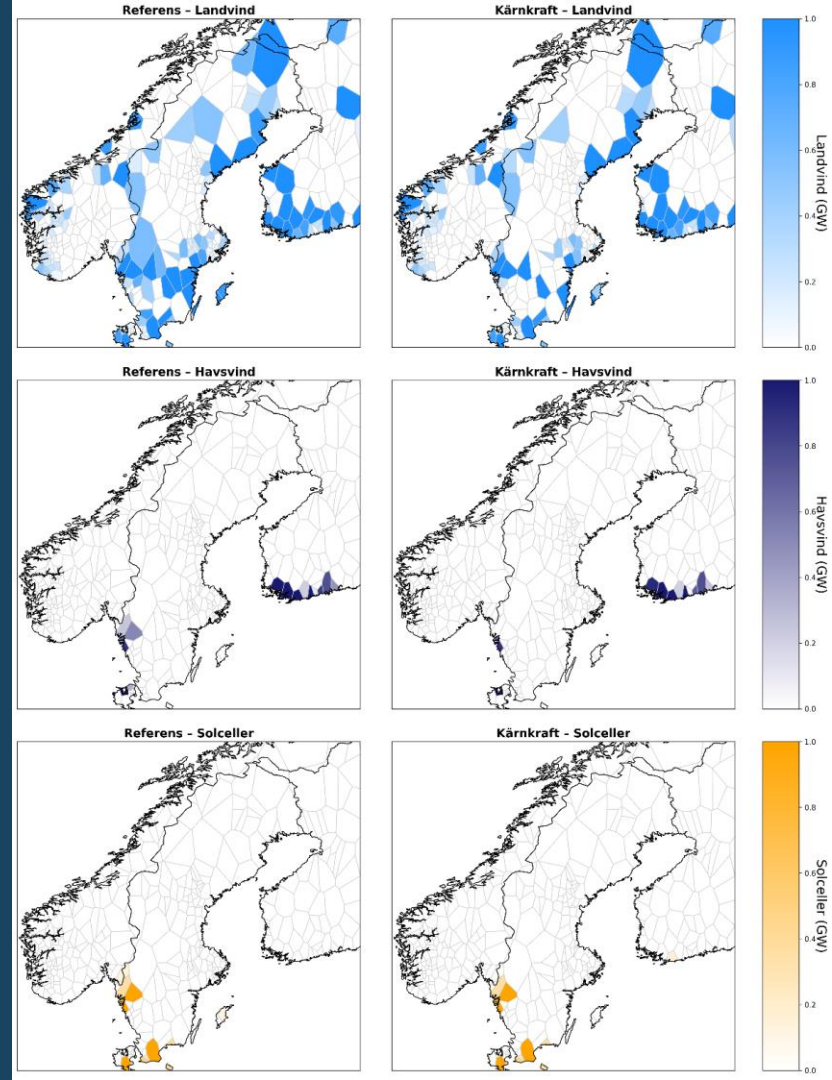
Generation & Storage

- Doubling of onshore wind power by 2035
- 50% VRE by 2035 on average, up to 75% instantaneous
- New nuclear power replaces wind and solar power in Sweden
- Heat storage
 - Replace HP in 1-2 days
- Hydrogen storage
 - Meet demand 3-4 days



Transmission Grid Constraints

- Low impact on installed capacity and annual generation
 - Location of onshore wind power adapted to grid constraints
 - Much lower solar PV capacity
- Load can meet generation with existing and planned transmission capacity
 - Generation planned at load centres
- New nuclear power reduces wind power in southern Sweden






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RP Checklist: Power & Energy System Scenarios

-  **Representation of demand flexibility, storage, and sector coupling**
 - These are incorporated in both capacity expansion models.

-  **Short-term balancing in order to assess the impact of wind and solar forecast uncertainty on the optimal energy mix**
 - The temporal resolution is sufficient to stimulate cost-efficient investments in flexibility, which act on the hour and longer timescales. To account for variability and uncertainty within the hour, a statistical post analysis is performed (see operational impacts).

-  **Grid limitations and stability constraints**
 - Detailed grid limitations are incorporated in one of the capacity expansion models, impacting the volume of solar PV investments.
 - Stability constraints are not taken into account in the capacity expansion models. Requirements for frequency control and voltage control under steady-state conditions are addressed in current work.

-  **Operational practices reflecting future system needs and services**
 - The Swedish study has these incorporated in both capacity expansion models.



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Resource Adequacy Estimates

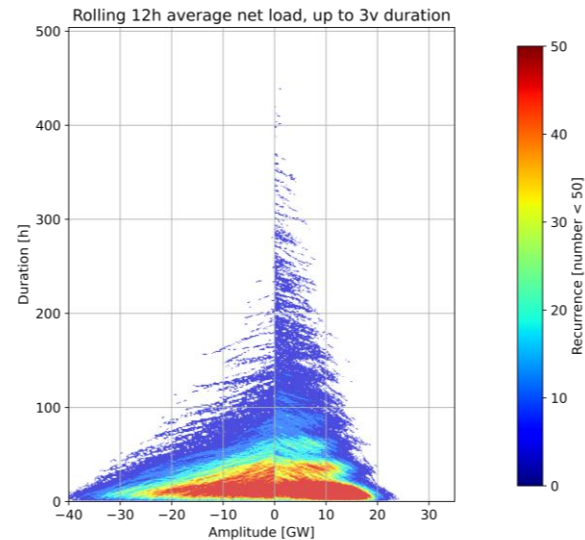
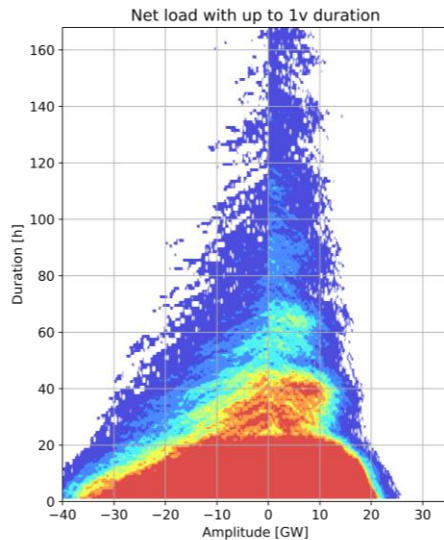
Swedish study in short:

Post-analysis of net load for 40 weather years

Assumption: Extreme events will be managed by gas turbines, and they have a low impact on total system composition

Extreme Net Load Events

- Variations can be defined by amplitude, duration and recurrence
- Power adequacy
 - +3 GW peak power
 - Individual HP + EV or gas turbines
- Longer high net load events
 - +2 GW with 3 days duration
 - Hydropower + existing nuclear power
 - Hydropower + gas turbines with fuel storage



RP Checklist 1/2: Resource Adequacy Estimates



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Include neighbouring areas and import possibilities (including forced outage rates) during times of generation scarcity.

- Neighbouring areas are well included in the calculations (even if without forced outage rates).



Consider the impact of inter-annual resource variability. Forward looking data should also account for climate change impacts. Temperature-correlated outages of thermal generators and common mode failures during extreme weather events should be captured.

- Capacity expansion simulations only consider a couple of years of data, but weather data analysis with 40 years of weather data is conducted to capture extreme cases.
- Climate change impact was not taken into account.



Include load and storage flexibility during times of high load and/or low energy resource using chronological models.

- Taken into account – future load flexibility in times of scarcity of wind/solar resource is assessed using a chronological model.

RP Checklist 2/2: Resource Adequacy Estimates



Use **multiple adequacy criteria and metrics** to fully identify, understand, and communicate risk, such as LOLH and LOLE, for event frequency and expected unserved energy (EUE).

- Resource adequacy was determined by mapping amplitude, duration and recurrence of the net load variability for 40 weather years.



Future load projections should account for the difference between electrification loads and existing loads as well as climate change impacts on demand profiles.

- New electrification loads are modelled.
- Climate change impacts on demand profiles are not taken into account.



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.

- This is not needed for reaching resource adequacy in this study.



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Transmission Network Steady-State Analyses

Swedish study in short:

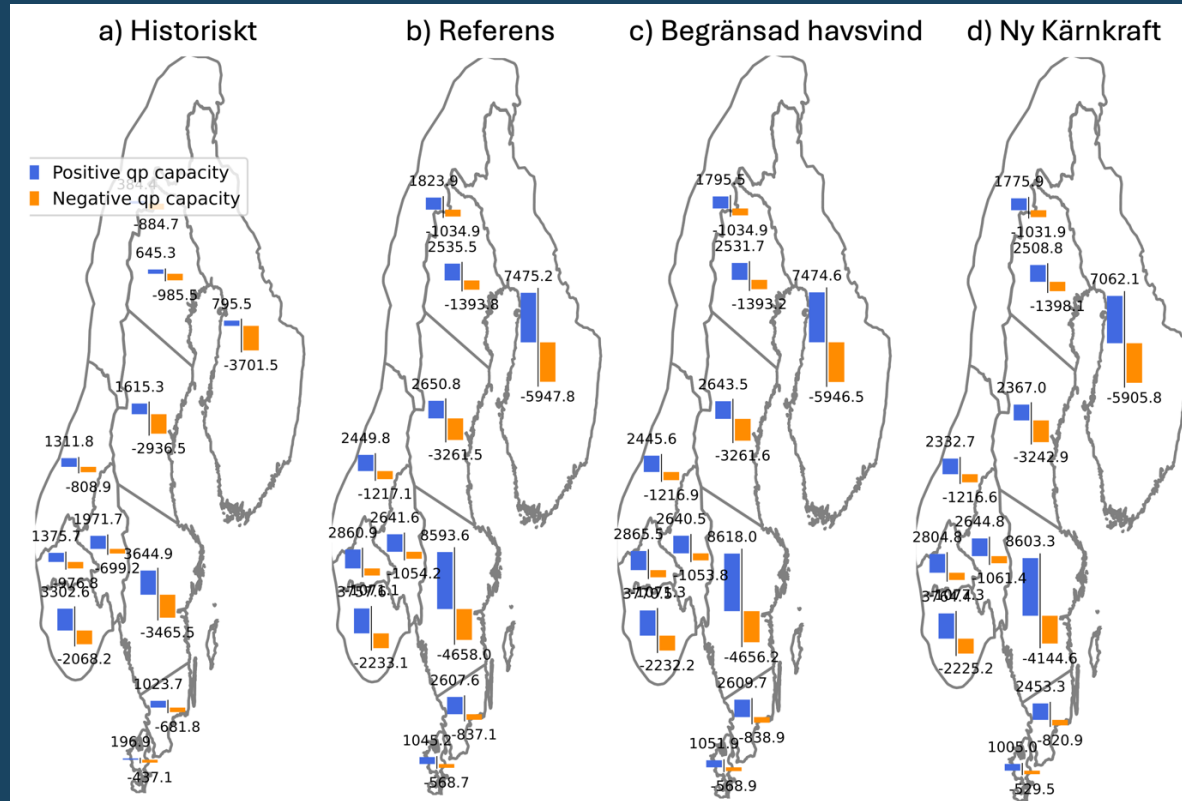
Full power flow simulations based on Nordic capacity expansion model results

400 nodes for 200-400 kV network

Assumption: Transmission grid limits ability to meet new load with new generation

Reactive Power Compensation

- Reactive power compensation under stable conditions is achieved using shunt capacitors and shunt reactors
- Change in location of loads and generation gives rise to changed needs
- Substantial increase in all future cases



RP Checklist: Transmission Network Steady-State Analyses



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Power flow cases to study: For higher wind and solar shares, probabilistic analysis is recommended allowing uncertainty and variability across a year to be captured.

- The flow of active and reactive power is simulated for all hours of one year in the Swedish case study.



Deterministic steady-state security analysis: power flow analyses are performed to identify transmission network bottlenecks and to assess the system's ability to maintain the voltage profile.

- The need for shunts for voltage control under steady-state conditions is part of the Swedish study.
- Dynamic voltage control for N-1 situations, as well as the benefits of incorporating dynamic line rating is ongoing work.



Short circuit levels: Screening tools should be applied to assess the grid strength across the network for an extensive range of operating conditions.

- Analysis of grid strength is not conducted in the Swedish study, but is included in future work.



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Operational Impacts

Swedish study in short:

High temporal resolution and multiple flexibility options in capacity expansion models

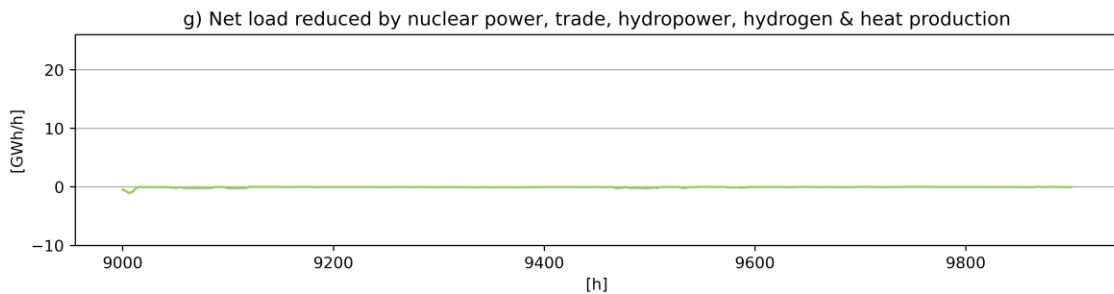
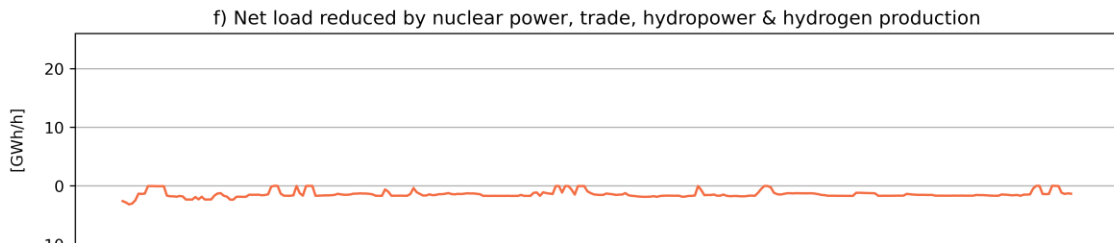
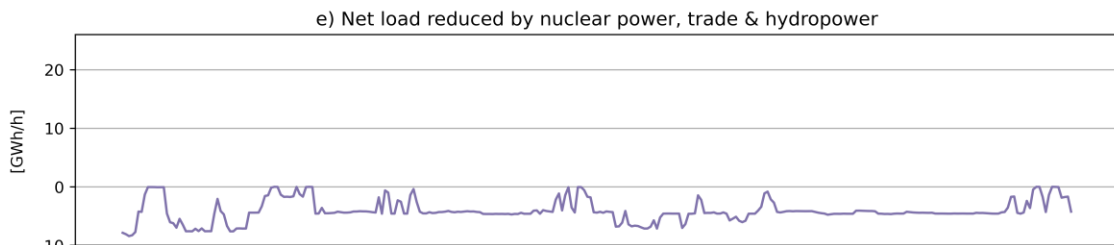
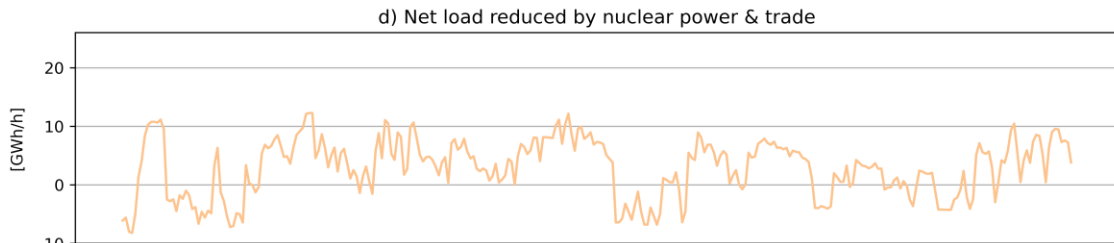
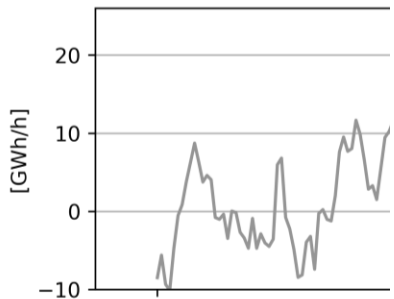
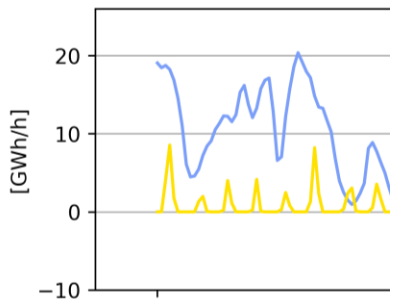
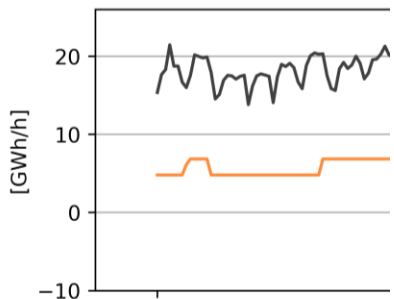
Assumption: The impact of variability on investments has a larger impact on future system costs and composition than the impact of uncertainty on operation

Post-analysis of variations within the hour

Assumption: Variations and uncertainty within the hour will be managed by batteries, and they have a low impact on total system composition

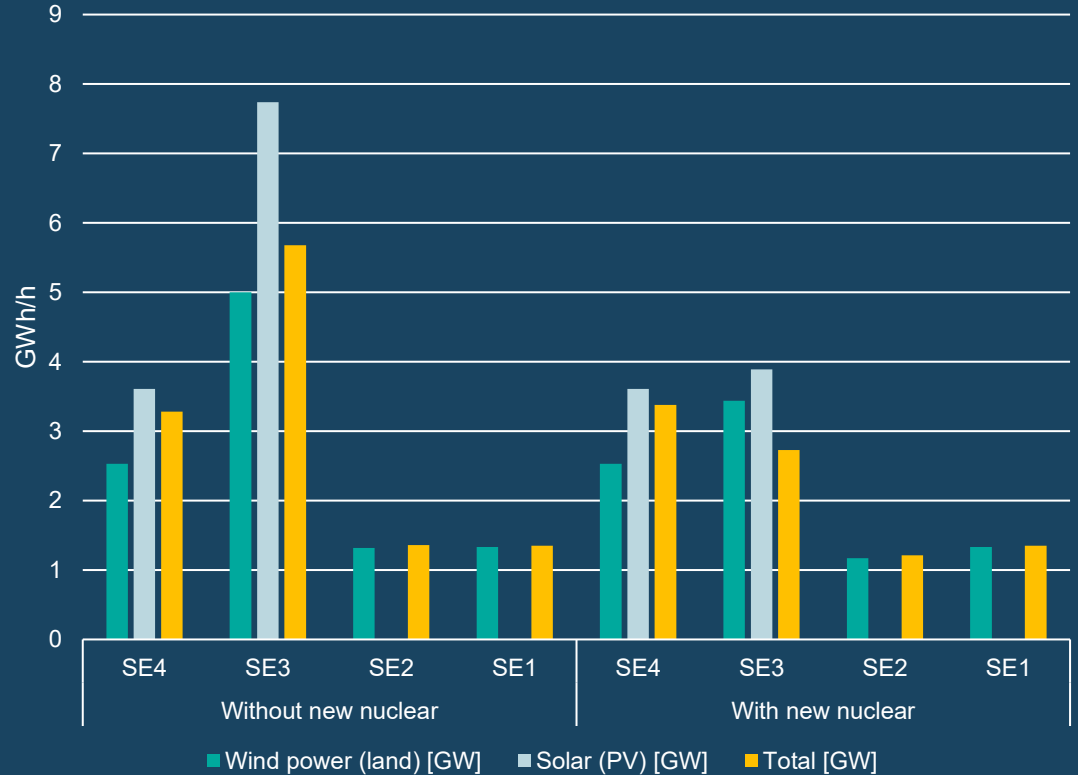
Man

- Collaborative
 - Trade
 - Hydro events
 - Heat and low wind
- No silver bullet
 - Cost-sensitive
 - Technological
 - Primary
- Good access to long duration
 - Match



Within the Hour

- VRE ramps
 - Solar PV presents the highest ramps
 - Worst ramps do not occur in the same hour
 - 3 GW/GWh more without new nuclear power



RP Checklist 1/3: Operational Impact



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Co-incident time series of wind/PV and load with sufficiently high temporal resolution to represent real (correlated) wind/PV power variations. For systems with significant hydropower, different hydrological scenarios should be considered.

- ELLI model: data from years 1991 (dry) and 1992 (wet), 2920 chronological clusters per year
- EHUB: data from year 2019 (normal), 3-hour time resolution



Capture generator/load responses including the impact of short- and long-term uncertainty on UCED dispatch decisions by introducing stochastic optimisation and rolling planning.

- With high temporal resolution in the capacity expansion models a separate UCED, accounting for forecast error, is not performed. The forecast error is assumed to be managed by operating reserves from the statistical analysis.



New operating reserve targets should be estimated based upon wind, solar, and load forecast uncertainty

- The need for operating reserves is assessed in post-analysis. The operating reserves are designed to cover needs within the hour which is not covered by the capacity expansion models.

RP Checklist 2/3: Operational Impact



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Model the capabilities and limitations of flexibility sources for generation, interconnections to neighbouring areas and sector coupling.

- Thermal cycling is included, but simplified to limit the minimum load for nuclear power.
- Neighbouring systems are included in the calculations.
- Flexibility from heating, electric vehicles and demand response are all included in the calculations.



Represent energy storage and price-responsive loads within system services.

- Strategic charging of electric vehicles is included using detailed data on vehicle movement to represent transportation needs and assure that charging needs are fulfilled. Potential limits in distribution grids of vehicle charging and discharging are not included.
- Individual heat pumps as system service providers are omitted.
- Due to the large hydro power and added storage and gas turbines in the future scenarios, additional system services are not considered critical.



Assess the flexibility of the existing power system, and apply indicators (metrics) to determine if additional flexibility options are sufficiently economically justified.

- Since operational aspects are included in the capacity expansion models the added flexibility (storage and gas turbines) are cost-efficient from a system point of view. Post-processing adds some gas turbines for resource adequacy and some storage for balancing.

RP Checklist 3/3: Operational Impact



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Model transmission system limitations, congestion and N-1 security constraints

- The EHUB capacity expansion model applies a detailed representation of the Nordic transmission grid and voltage angle as well as thermal limits on transmission.
- The need for investments to achieve frequency control and voltage control under steady-state conditions are assessed separately.



In systems with very high levels of renewable generation, it may also be necessary to model additional stability constraints.

- Due to the continuous operation of hydropower in the Nordic grid, no inertia floor is needed. The increased need for fast feed in of active power to compensate for inertia loss is accounted for.
- The need for stationary batteries and shunts to assure frequency and voltage control under normal operation is included.



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Network and Dynamics Simulations

Swedish study in short:

Undergoing development of dynamic models based on the Nordic 400 nodes power flow model of the 200-400 kV network

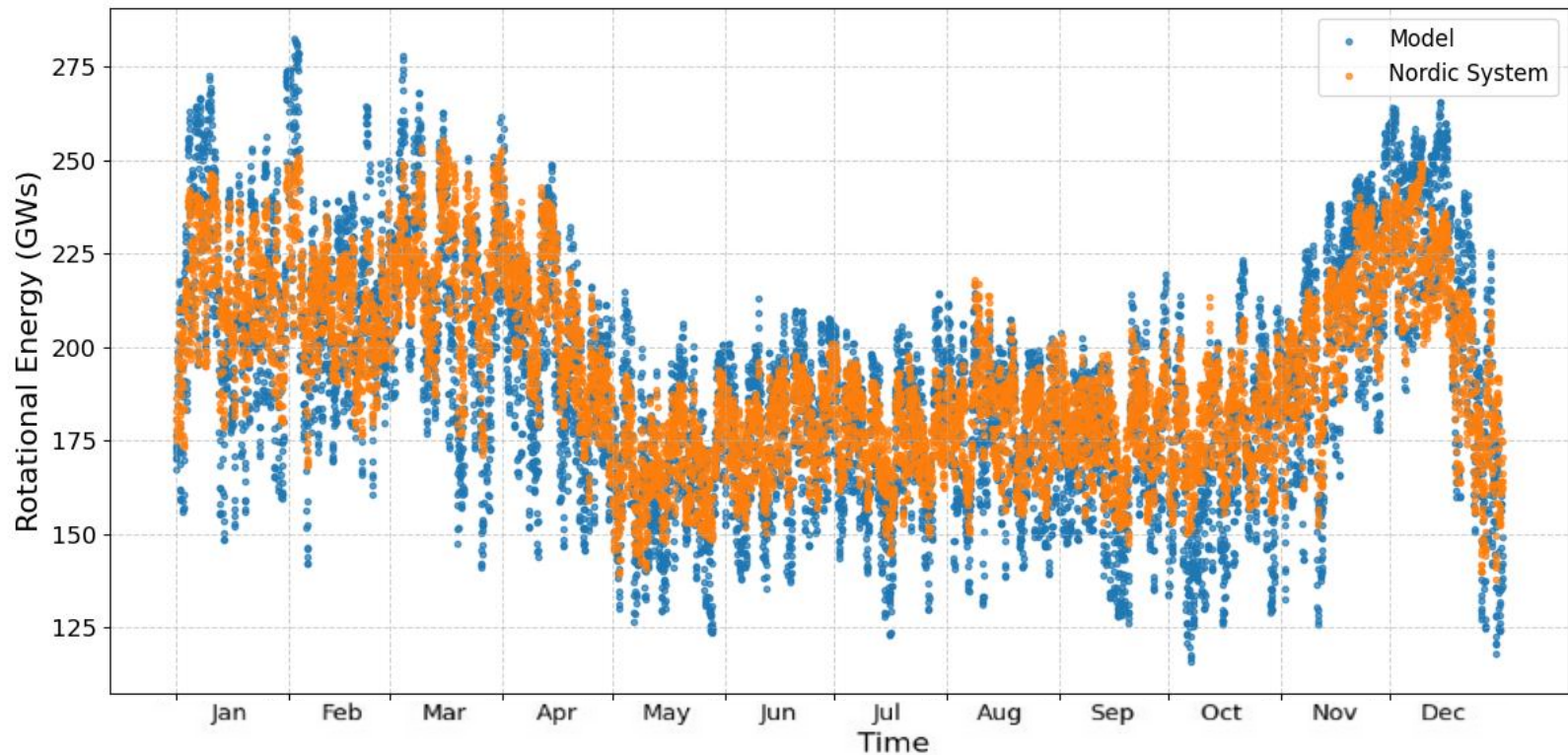
Assumption: System stability requirements under contingency events impose additional constraints on the generation dispatch scenarios

ROCOF and System Inertia

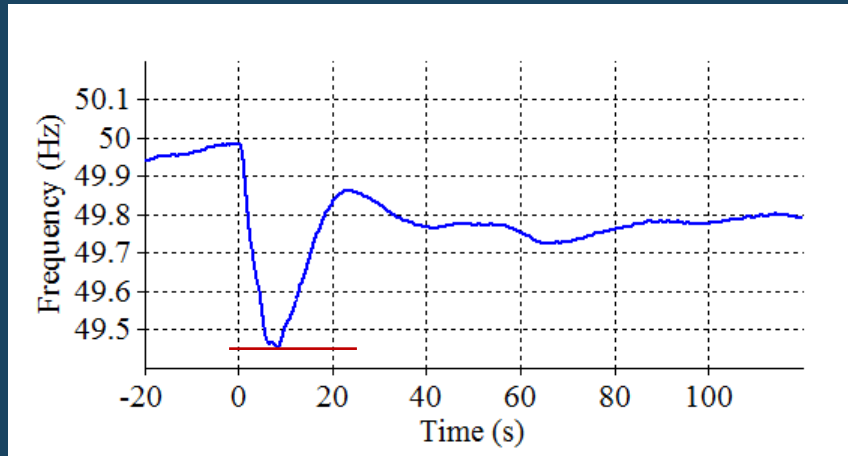
Maximum allowed system RoCoF in Nordic
Synchronous Power System: **2 Hz/s**

Minimum rotational energy (GWs) needed
in the Nordic system to limit the RoCoF

Rotational Energy in the Nordic 400 Nodes Model - 2022



Frequency Nadir



- Frequency nadir is determined by
- Size of disturbance
 - System inertia
 - Frequency containment process
 - Load frequency (and voltage) dependence

RP Checklist: Network and Dynamics Simulations 1/3



+ **Selecting snapshot cases for analysis:** An initial screening of cases can be conveniently performed using RMS modelling, but detailed EMT analysis is required for high IBR shares.

- Cases considered for dynamic simulation include high IBR shares, high/low load conditions, high north-south flow, high south-north flow, high east-west flow, high west-east flows, etc.

+ **Frequency stability studies:** Inertial constant, droop, and governor settings of all synchronous units are needed, along with assessing the system's ability to maintain a satisfactory voltage profile.

- System hourly rotational energy in the 2022 model matches well with data published by Fingrid.
- Droop and governor models for synchronous generators and frequency controllers for power park modules represent ongoing work.

× **Voltage stability studies:** For 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.

- Incorporating AVR and exciter models for synchronous generators, and V/Q controllers for power park modules are ongoing work.


RP Checklist: Network and Dynamics Simulations 2/3





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-  **Transient stability studies:** include the effect of protection devices for both network and converter-interfaced generating equipment. Wind, BESS, and solar generation can provide system support during voltage dips and help to dampen oscillations
 - Voltage-ride through studies will be conducted after the dynamic models of the synchronous generators and power park modules are built for the Nordic system model.

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

-  **Resonance stability studies:** Sub-synchronous torsional interaction and sub-synchronous control interactions 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.
 - Swedish (and Finnish) power grids have several series-compensated lines, which make it relevant to evaluate sub-synchronous resonance stability.


RP Checklist: Network and Dynamics Simulations 3/3




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-  **Converter-drive stability studies:** Models capable of capturing the harmonic power dynamics, especially in multi-converter setups, are crucial
 - Highly relevant studies for the Swedish power system, and they are planned after completing the frequency and voltage stability studies.

-  **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. 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 lead to a common-mode power reduction and frequency stability issues, such as voltage dip induced frequency dips.
 - The study of N-1-X contingency events, such as voltage dip induced frequency dips, are relevant studies for the Nordic system, with many distributed generators connected to distribution grids, and they are currently under study in a different project.



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Analysing and Presenting Results

Swedish study in short:

Two ways of meeting the demand for electricity in future Swedish systems are compared, with and without minimum investment level in new nuclear power capacity

Conclusions on Costs for a VRE Dominated Swedish System

- More storage, battery and gas turbine capacity is needed in a future SE electricity system without new nuclear power
- High importance to map these needs and create incentives / regulations to put these in place
- The cost of these components is significantly smaller than the additional cost of new nuclear power
- Future work includes
 - Dynamic reactive power compensation (n-1)
 - Analysis of impedance and need to compensate for “weak grid” conditions
 - System stability model

	No new nuclear power	New nuclear power	Additional cost w. nuclear power [MEUR/år]
Production and storage	+200 GWh hydrogen and heat storage +8 GW wind power +12 GW solar power	+6GW kärnkraft	770-1600 MEUR/år
Power reserve	+1.1 GW gasturbine capacity in SE4	No need	-53 MEUR/år
Extreme Netload events	Underestimate peak power need with 3GW. Can be compensated for by flexible charging of EV:s (3,4 GW) and flexible operation of individual heat pumps (5GW) +0-1.9 GW gas turbine capacity to manage long duration events.	Underestimate peak power need with 3GW. Can be compensated for by flexible charging of EV:s (3,4 GW) and flexible operation of individual heat pumps (5GW)	-(0-74) MEUR/år
Flexibility to manage grid bottlenecks at 200-400kV level	With strategic placement of new generation this can be avoided.	With strategic placement of new generation this can be avoided.	0
Voltage control	Increased need of shunt capacitors caused by occasions with high loading on long lines.	Increased need of shunt capacitors caused by occasions with high loading on long lines.	-2 MEUR/år
Within the hour	Battery capacity to manage ramps of VRE 12 GW/12GWh Battery capacity for fast feed in of active power 0.6 GW/0.2GWh	Battery capacity to manage ramps of VRE 9 GW/9GWh	-40 MEUR/år





RP Checklist: Analysing and Presenting Results



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-  If the results show unexpectedly high and costly impacts of wind/PV power to the system, consider the iteration loops.
 - This was not needed, since operational aspects are included directly in the capacity expansion models and the costs of additional components needed are relatively small.
-  When extracting results for the impacts, select the cases to compare with care. Comparing full scenarios are recommended, instead of extracting cost differences as integration costs.
 - Comparison of two cases, with new nuclear or new wind/solar energy, was performed with full scenarios
-  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.
 - The Swedish study presents both system composition and geographical VRE distribution.
-  List main assumptions and limitations arising from these.
 - Included in the report of the Swedish study
 - Limitations of the modelling methodology are clearly described in the study report.

Suggestions to Facilitate High Quality Integration Studies

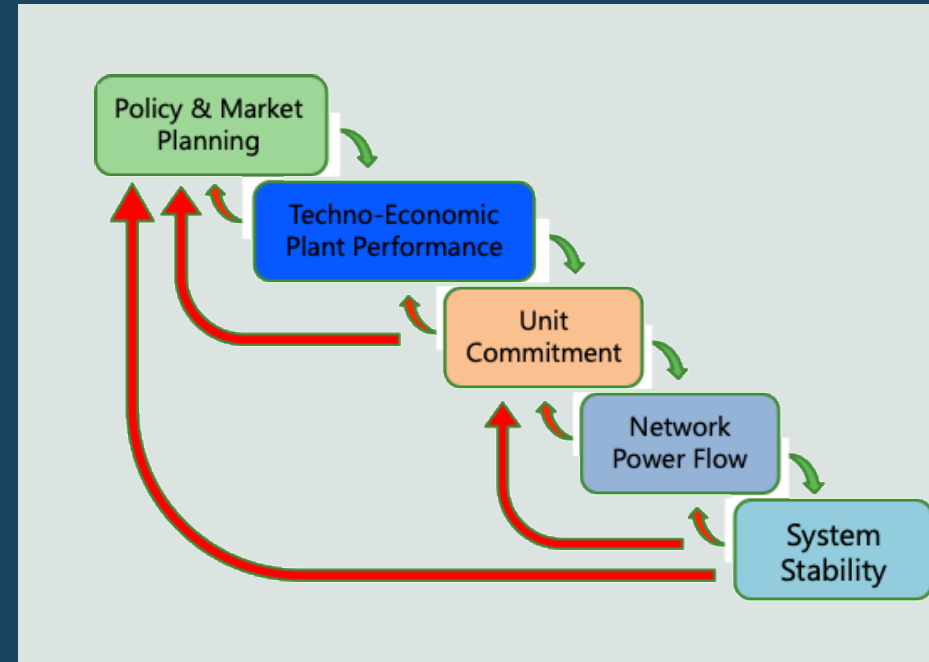


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- Collaboration is required!
 - Carrying out a complete wind and solar integration study requires both energy systems and electrical power engineering expertise
- Openly shared modules could open doors
 - Multiple tools are required and could be overwhelming for small research teams
 - Modules shared in the community which can be flexibly integrated with different CEM and UCED models
 - Reserve requirements to cover uncertainty incl. forecasts
 - Resource adequacy over weather years incl. climate data
- Investigate consequences of missing out on steps & selecting simplified approaches
 - Help to prioritise and simplify
 - Better understand and interpret results





Future Work - Evolution of Methodologies

Integration studies are becoming general system studies for the energy transition

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



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Thank you for your attention

Recommended Practices for wind and solar integration studies, Ed.3, available at <https://iea-wind.org/publications/>

iea-wind.org/wp-content/uploads/2025/02/RP-16-Ed-3-Wind-PV-Studies_final_2a.pdf