Recommended Practices in practice

How to include wind and solar in system studies

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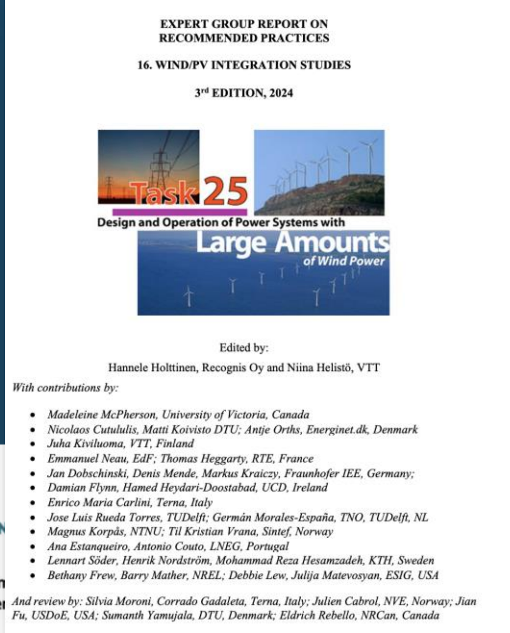
Compare practice to recommendations

- 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



EXPERT GROUP REPORT ON
RECOMMENDED PRACTICES

16. WIND/PV INTEGRATION STUDIES

3rd EDITION, 2024

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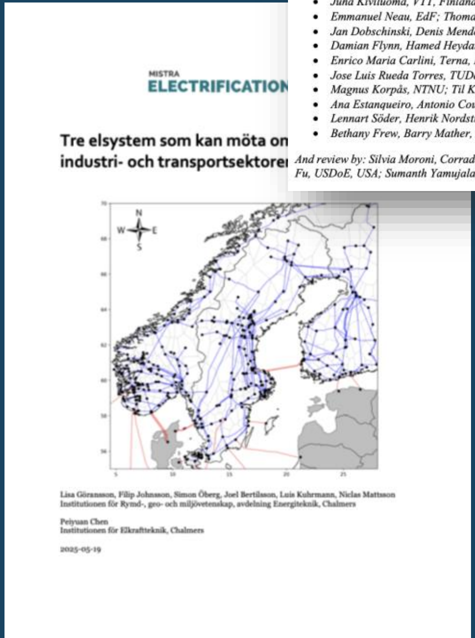

MISTRA
ELECTRIFICATION

Tre elsystem som kan möta on
industri- och transportsektorer

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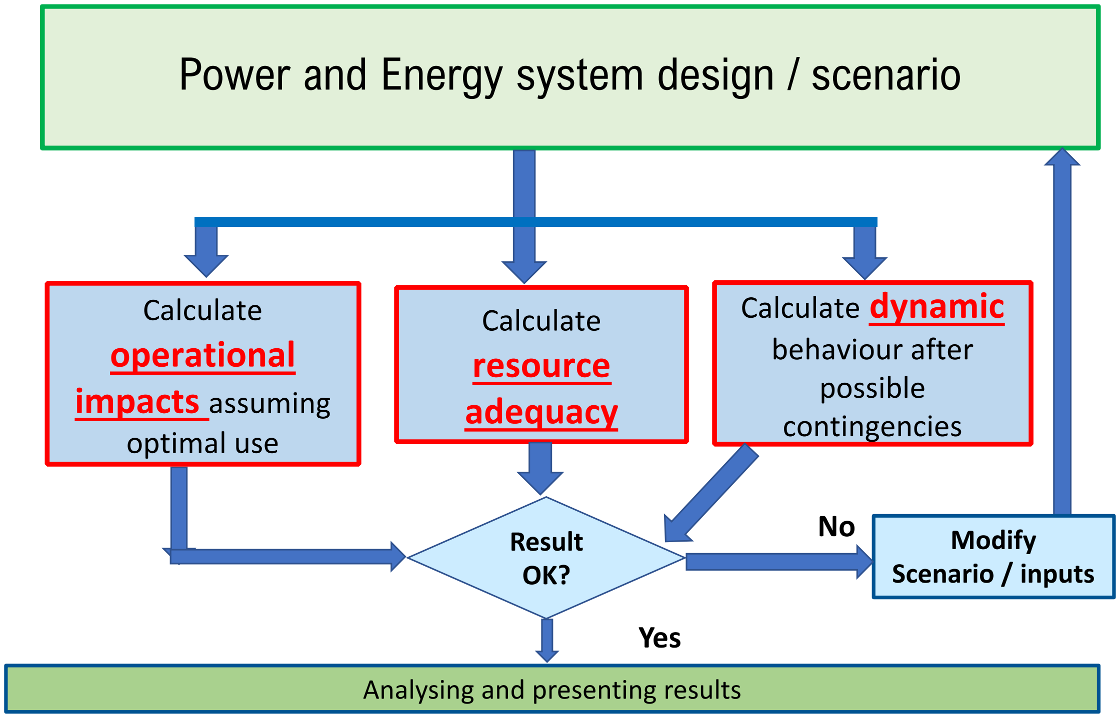
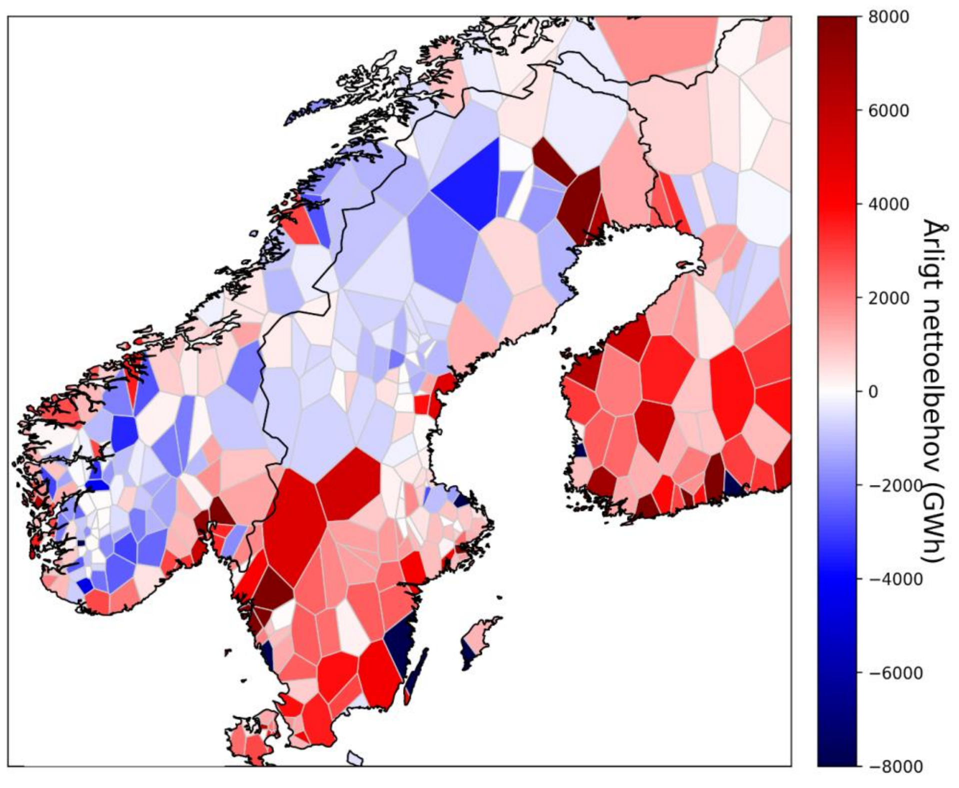
Context: Recommended practices RP

- 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)



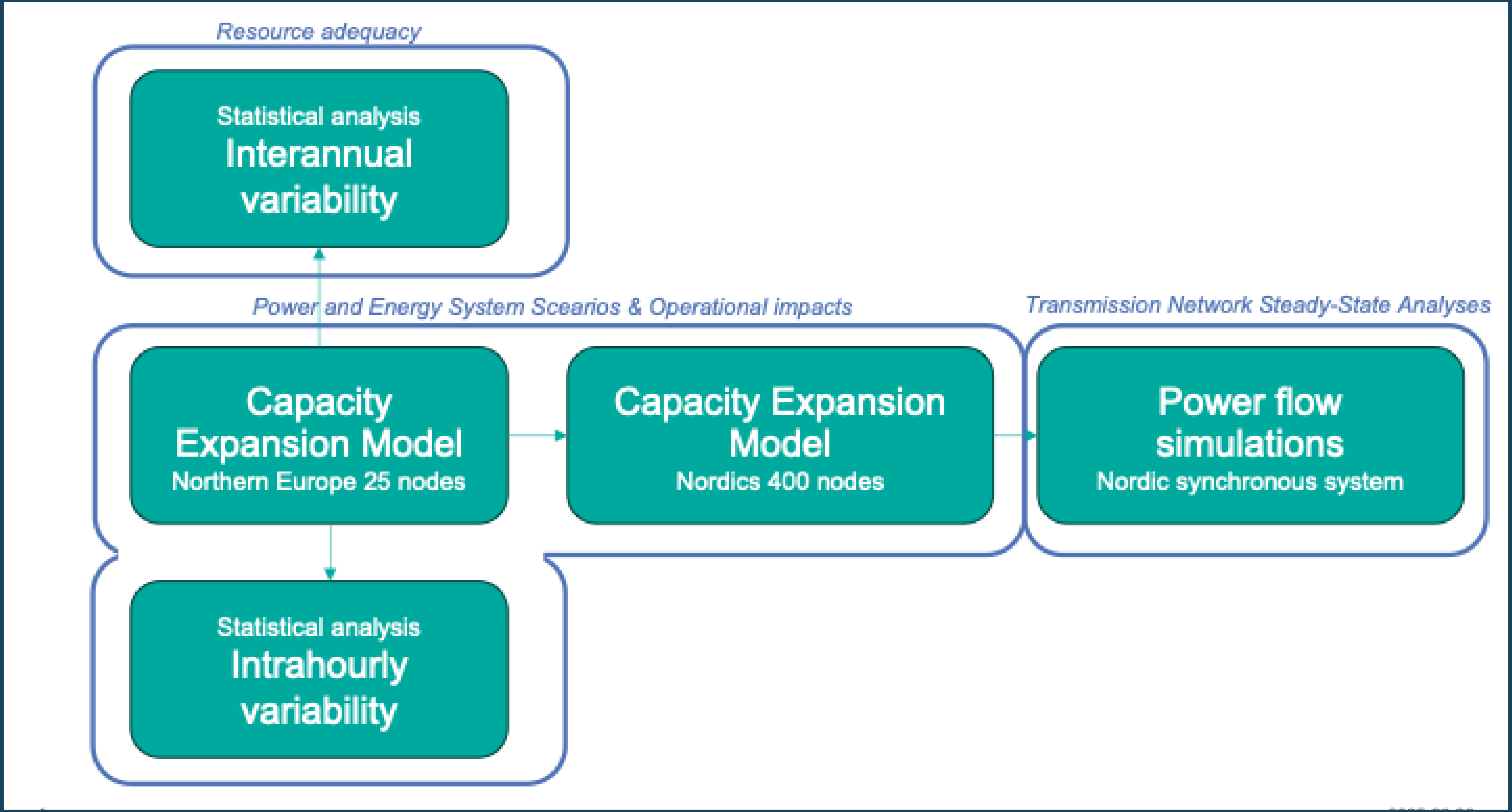
Context: Chalmers study on Electrification in Sweden

- Climate neutral by 2045
- Increased electricity demand from energy-intensive industry
  - Iron and steel
  - Refinieries
  - Plastics
  - Cement
  - Batteries for car manufacturing
- A supply-side dominated by wind and hydropower
- How can the electricity/hydrogen/heat demand be met to lowest cost for society?
- What is the full cost of a wind dominated system?



Modeling framework

Model	Aim	Geography	Time	Sectors	Results
ELLI	Minimizing the cost to society to meet demand	Large part of Europe divided into 25 bidding zones	Every 5 years 2030-2065 Two weather years 2920 time clusters per year	Electricity, hydrogen and district heating	Electricity production mix over time Size of hydrogen storage and heat storage Marginal cost of electricity and hydrogen
EHUB	Minimizing the cost to society to meet demand	Nordic synchronous system divided into 400 nodes	2050 A weather year 3h time resolution	Electricity, hydrogen and district heating	Localization of new electricity generation and storage Impact of transmission grid capacity on production mix
Power flow model	Simulate flows of active and reactive power	Nordic synchronous system divided into 400 nodes	2050 A weather year 3h time resolution	Electricity	Checking that calculated electrical systems can comply with physical laws on active and reactive power in normal operation Need for reactive power compensation in a stable state



Resource adequacy
Statistical analysis
Interannual variability
Power and Energy System Scearios & Operational impacts
Transmission Network Steady-State Analyses
Capacity Expansion Model
Northern Europe 25 nodes
Capacity Expansion Model
Nordics 400 nodes
Power flow simulations
Nordic synchronous system
Statistical analysis
Intrahourly variability

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 Simulations for Dynamics
- Analysing and Presenting Results

Power & Energy system scenarios

Swedish study in short:

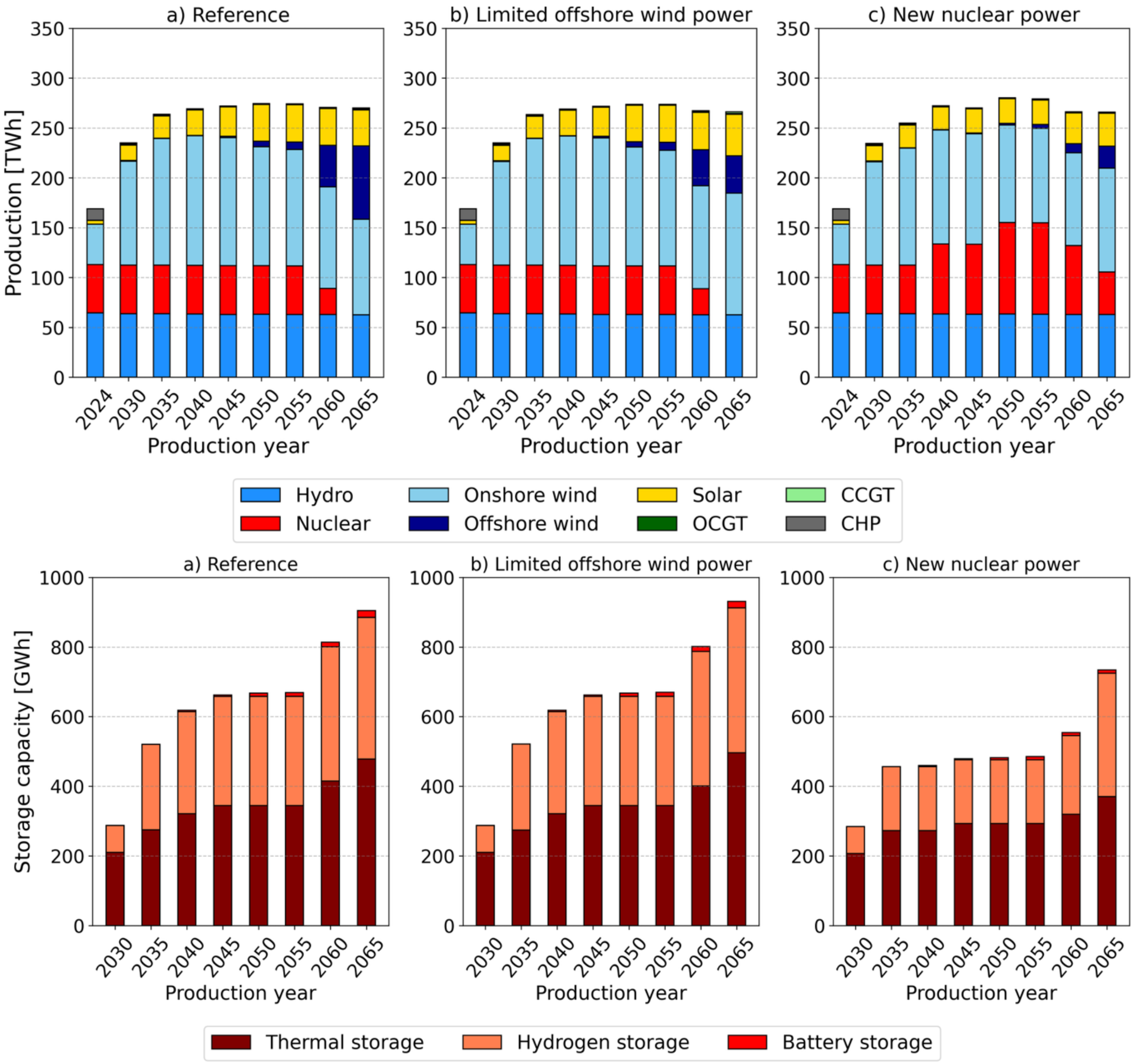
2 capacity expansion models, both with high temporal resolution, one with long time span and one with high geographical resolution

2 cases compared –with and without new nuclear power

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

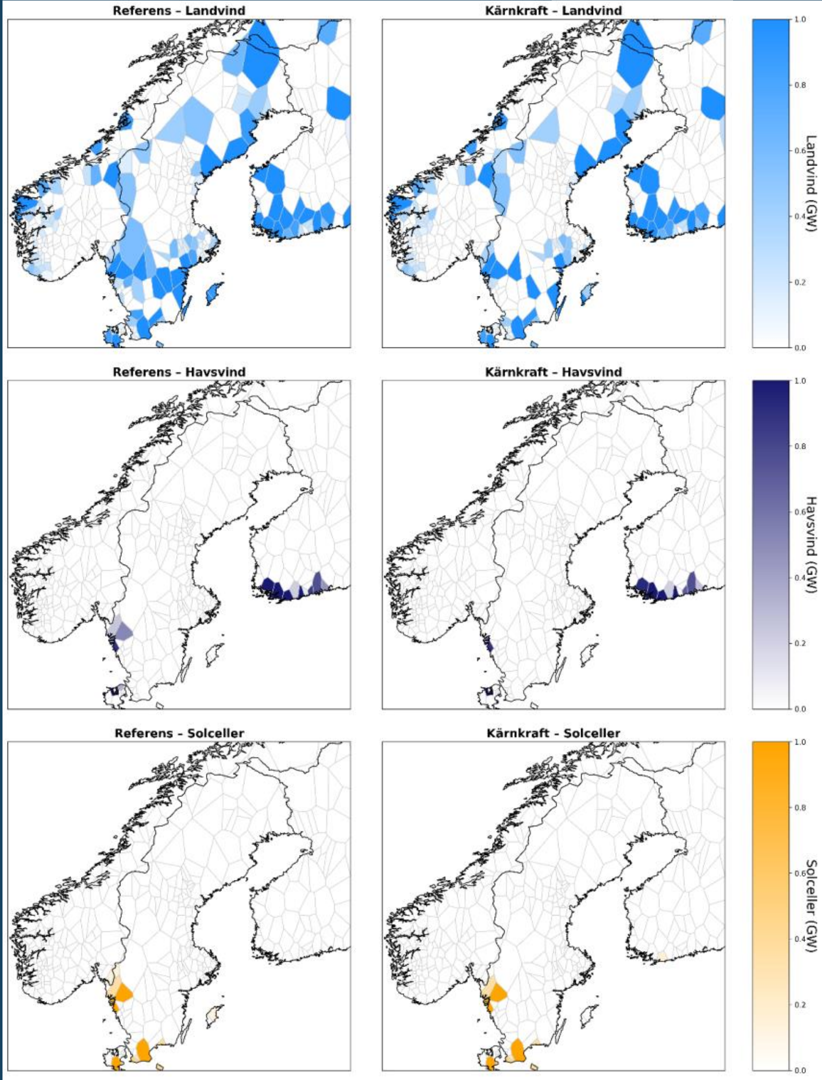
Generation & storage

- Doubling of onshore wind power by 2035
- 50% VRE by 2035
- 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
  - 50 % over capacity of electrolyser
  - Reduced by new nuclear power



Transmission grid constraints

- Low impact on installed capacity and annual generation
  - Location of onshore wind power adapted to grid constraints
  - Mucher low solar PV capacity
- With limited temporal scope gives lower cost of new nuclear power
  - Build the system to fit level of nuclear capacity
- New nuclear power reduce wind power in south Sweden



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 up. 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 amount of solar PV investments.
- The 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 subsequent steps.

Operational practices reflecting future system needs and services. ✓

- The Swedish study has these incorporated in both capacity expansion models.

Resource Adequacy Estimates

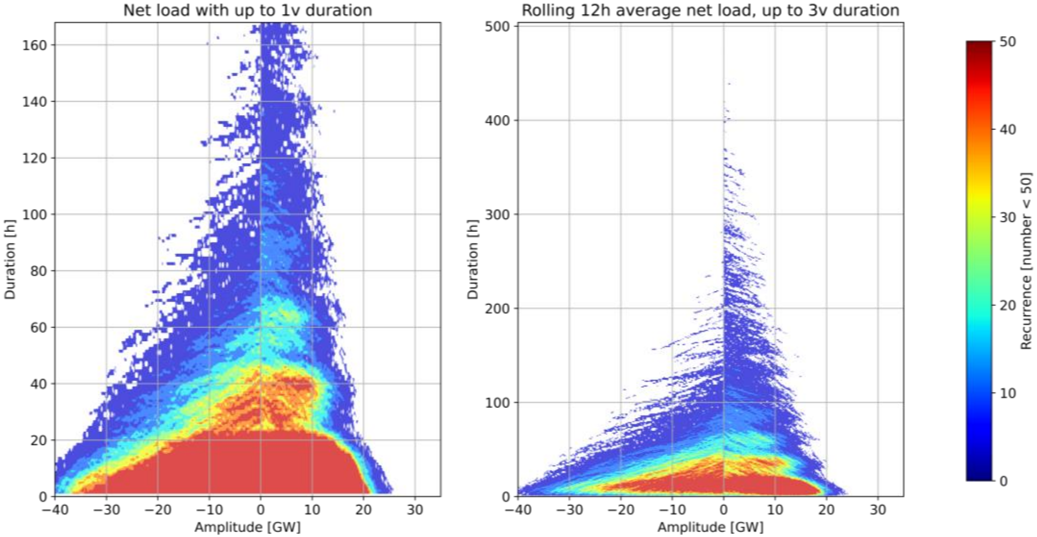
Swedish study in short:

Post-analysis of net load for 40 weather years

Assumption: Extreme events will be manged by gas turbines and have low impact on total system composition

Extreme net load events

- Power adequacy
  - Maximum load over 40 years is 29,5 GW
  - Maximum net load over 40 years is 27 GW
  - Maximum net load for modeled years is 24 GW
  - Short duration & low recurrence
  - Individual HP + EV or gas turbines
- Longer high net load events
  - 17 GW for 3 days (40 years)
  - 15 GW for 3 days (modeled years)
  - Hydropower + existing nuclear power
  - Hydropower + gasturbines w. fuel storage



RP Checklist 1/2: Resource Adequacy Estimates

✓ **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 are only using a couple of years of data, but a weather data analysis with 40 years of weather data is conducted to see for the 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.

- This is taken into account – future load flexibility in times of scarcity of wind/solar resource with chronological model.

RP Checklist 2/2: Resource Adequacy Estimates

- ✓ Use **multiple adequacy criteria and metrics** to fully identify, understand, and communicate risk like 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.

Transmission Network Steady-State Analyses

Swedish study in short:

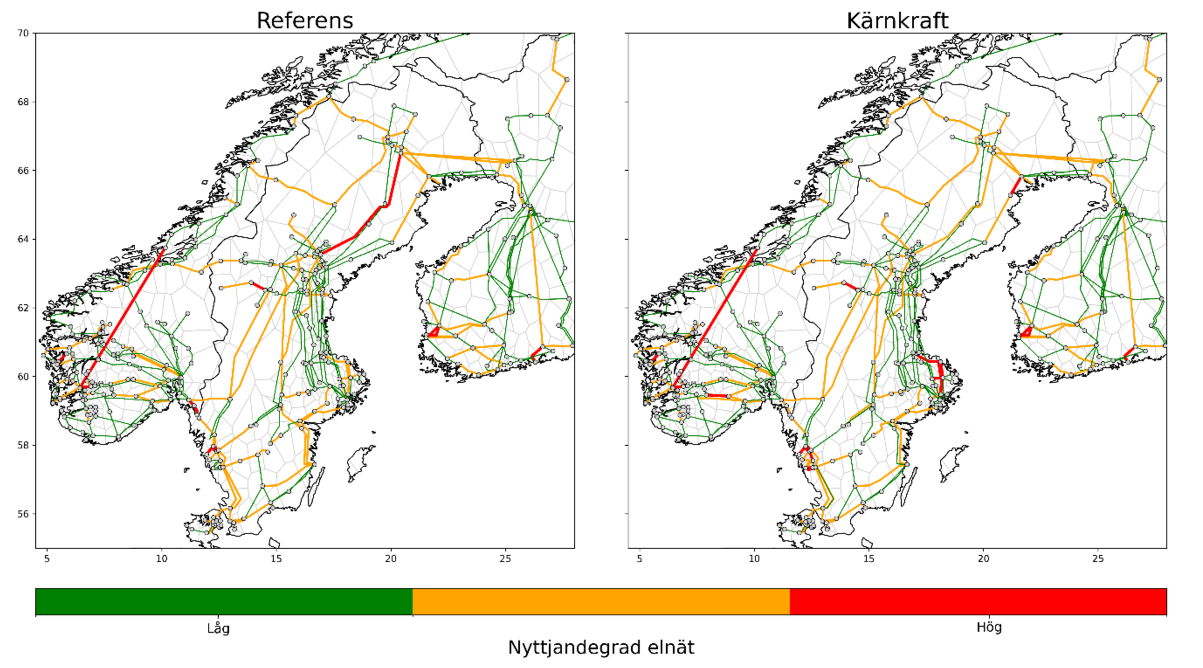
Full power flow simulations based on Nordic capacity expansion model results

400 nodes in 200-400kV network

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

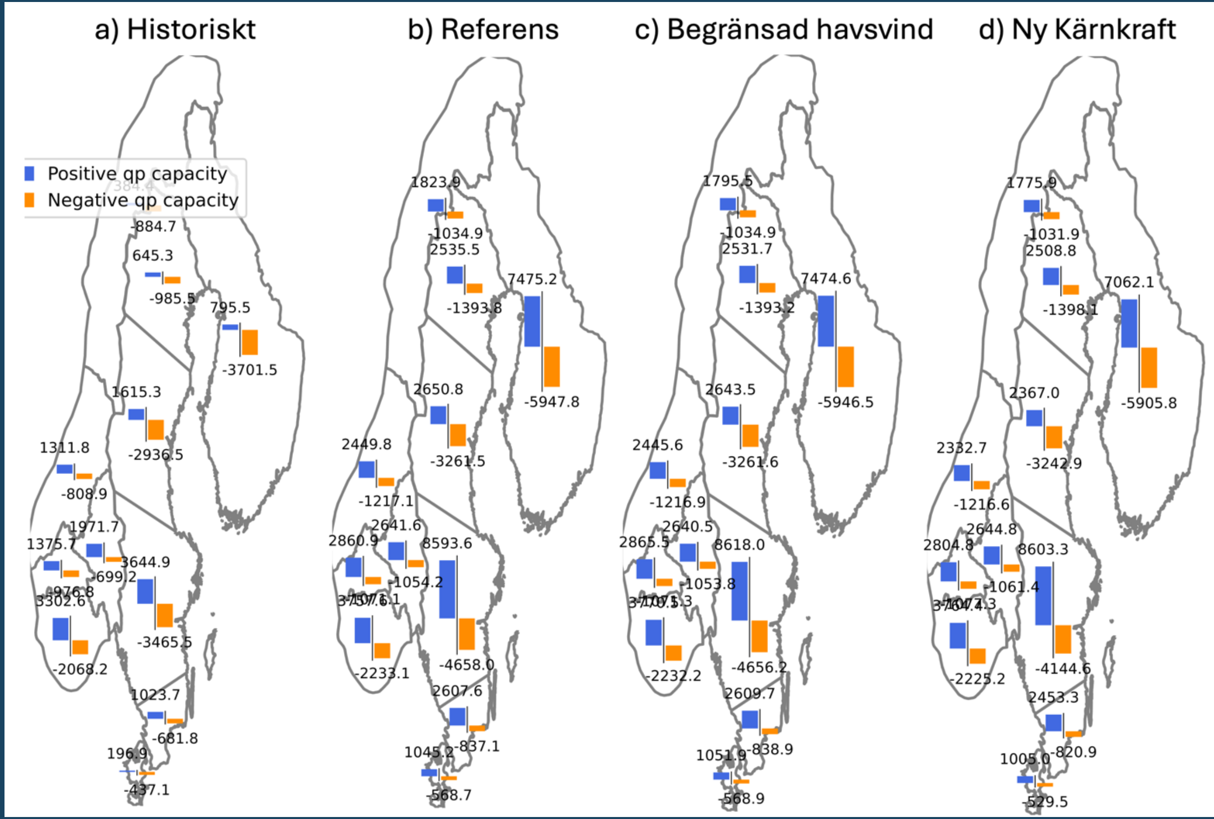
Utilization of transmission grid

- Medium to low utilization on average
- Combinations of hours with high and low utilization
- In model world location is adjusted to grid capacity
- New nuclear power has low impact on utilization



Reactive power compensation

- Reactive power compensation under stable conditions is done with shunt capacitors and shunt reactors
- Change in location of loads and generation gives changed needs
- Substantial increase in all future cases
- Without new nuclear power
  - +1120 MVAr shunt capacitors
  - +620 MVAr shunt reactors
  - 2 MEUR/yr



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 stead-state conditions is part of the Swedish study.
- Dynamic voltage control for N-1 situations as well as benefits of 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 plans.

HVDC grids: DC power flow for uncontrolled mesh networks.

- The AC power source approach is applied in the power flow analysis in the Swedish study.

Operational Impacts

Swedish study in short:

High temporal resolution and multiple flexibility options in capacity expansion models

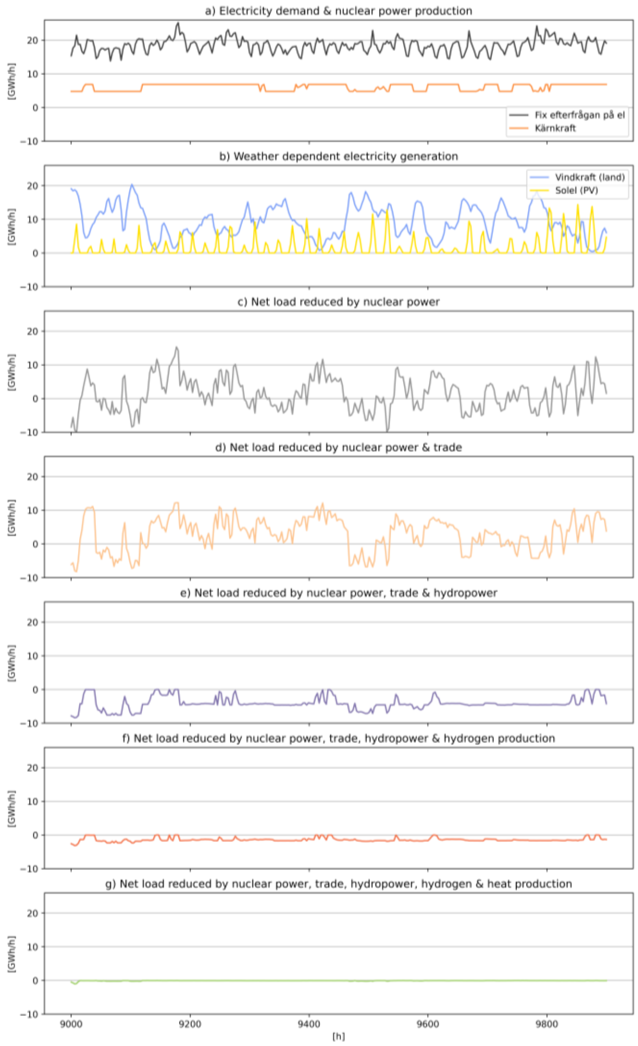
Assumption: The impact of variability on investments has larger impact on future system costs and composition than the impact of uncertainty on operation

Post-analysis of variations within the hour

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

Managing variability

- Collaboration between flexibility resources
  - Trade reduces net load peaks
  - Hydropower reduces positive short & long net load events
  - Heat and hydrogen production is avoided during low wind events
- No silver bullet
  - Cost-structure
  - Technical properties
  - Primary purprose
- Good access to flexibility resources suitable for variations of long duration in the Swedish context
  - Matches well with the wind resource



Within the hour

- Ramps of VRE
  - Solar PV has highest ramps
  - Worst ramps do not occur the same hour
  - 3 GW/GWh more without new nuclear power
- Fast feed-in of active power in case of a fault
  - Compensate for loss of inertia
  - 1/3 of Nordic 1450 MW
  - Sustain for 20 min
- 3,6 GW / 3,2 GWh of batteries for approx 40 MEUR/yr

	Without new nuclear				With new nuclear			
	SE4	SE3	SE2	SE1	SE4	SE3	SE2	SE1
Wind power (land) [GW]	2,53	5,00	1,32	1,33	2,53	3,44	1,17	1,33
Wind power (sea) [GW]	0,55	0	0	0	0,18	0	0	0
Solar (PV) [GW]	3,61	7,74	0	0	3,61	3,89	0	0
Load [GW]	0,12	0,28	0,039	0,019	0,12	0,28	0,039	0,019
Total [GW]	3,28	5,68	1,36	1,35	3,38	2,73	1,21	1,35

RP Checklist 1/3: Operational impact

✓ **Co-incident time series of wind/PV and load** with sufficiently high temporal resolution and 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 no separate UCED is performed with the drawback that the impact of forecast error was omitted.

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

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

RP Checklist 2/3: 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 be also 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.

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

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

RP Checklist 3/3: Operational impact

Assess the existing flexibility of the power system, and apply indicators (metrics) to determine whether 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 system point of view. The post processing adds some gas turbines for resource adequacy and storage for balancing.

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 this is fulfilled. Potential limits in distribution grids of vehicle charging and discharging is 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 critical.

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 of a VRE dominated Swedish system

- More storage, battery and gasturbine 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 from new nuclear power
- Future work includes
  - Dynamic reactive power compensation (n-1)
  - Anlaysis of impedence and need to compensate for "weak grid"
  - System stability model

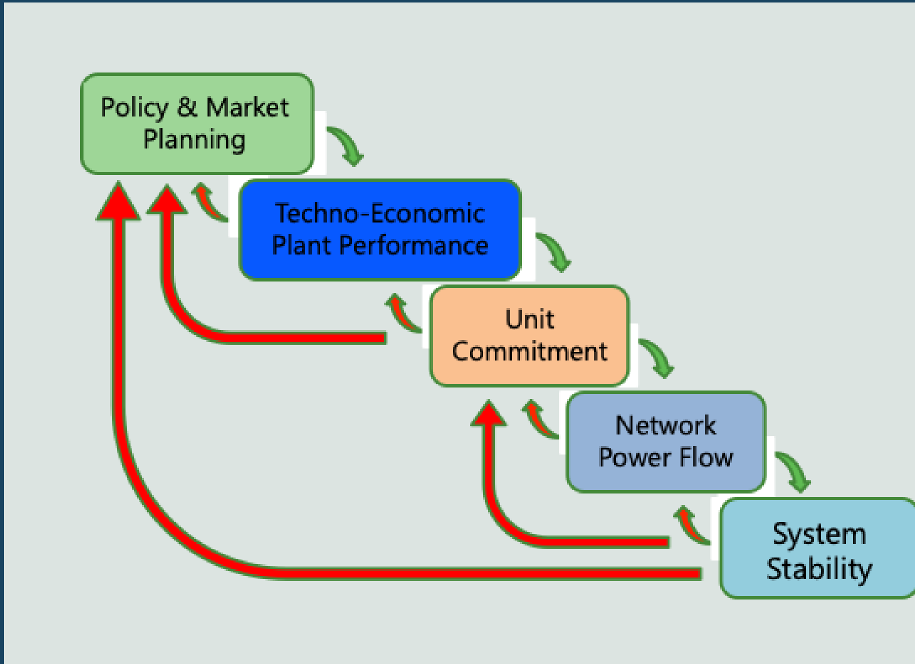
	No new nuclear power	New nuclear power	Additional cost w. nuclear power [MEUR/år]
Production and storage	+200 GWh hydrogen and heat storage +8 GW wind power +12 GW solar power	+6GW kärnkraft	770-1600 MEUR/år
Power reserve	+1.1 GW gasturbine capacity in SE4	No need	-53 MEUR/år
Extreme Netload events	Underestimate 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

- ✓ 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 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 done 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 distribution of VRE.
- ✓ List main assumptions and limitations arising from these.
  - This is included in the report of the Swedish study
  - Limitations of the modelling methodology is also clearly described in this paper.

Suggestions to facilitate high quality integration studies

- Collaboration is required!
  - Carrying out a complete wind and solar integration study requires both energy systems and electric 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 approches
  - Help to prioritize and simplify
  - Better understand and interpret results



IEA Wind TCP

Future work - evolution of methodologies

Integration studies are becoming general system studies for 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

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