The market value of wind power in the Nordic region

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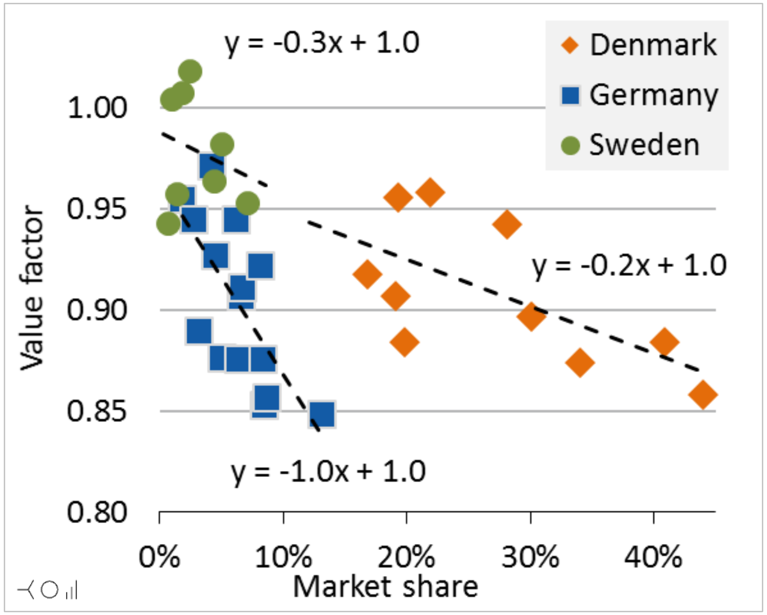
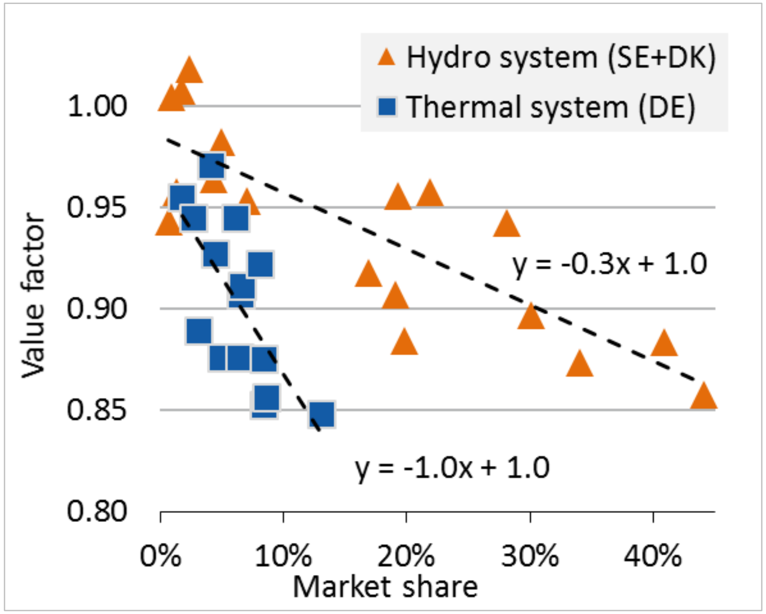
This study

- A project for Energiforsk
- Updated version published in Applied Energy

Market value in the Nordics: market data

Empirical value factors





Neon analysis.

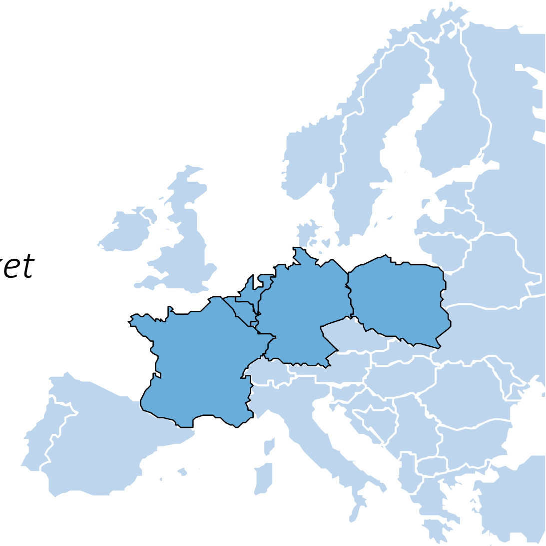
In Sweden and Denmark, value factors have been much mores table than in GER.

Grouped together, SE+DK value factors decline at a third the rate than in GER.

Modeling hydro power in EMMA

The Electricity Market Model EMMA

Numerical partial-equilibrium model of the European interconnected power market



Objective: minimize system costs

- Capital costs
- Fuel and CO2 costs
- Fixed and variable O&M costs
- ... of power plants, storage, interconnectors

Decision variables

- Hourly dispatch
- Yearly investment
- ... of plants, storage, interco’s

Constraints

- Energy balance
- Capacity constraints
- Volume constraints of storage
- Balancing reserve requirement
- CHP generation
- (No unit commitment, no load flow)

Resolution

- Temporal: hours
- Spatial: bidding areas (countries)
- Technologies: eleven plant types

Input data

- Wind, solar and load data of the same year
- Existing plant stack

Equilibrium

- Short-/mid-/long-term model (= dispatch / capacity expansion / greenfield)
- Equilibrium (“one year”) rather than a transition path (“up to 2030”)

Economic assumptions

- Price-inelastic demand
- No market power
- Carbon price

Implementation

- Linear program
- GAMS / cplex

Applications

- Four peer-reviewer articles
- Various consulting projects
- Copenhagen Economics

Open source


Motiv från Porjus.

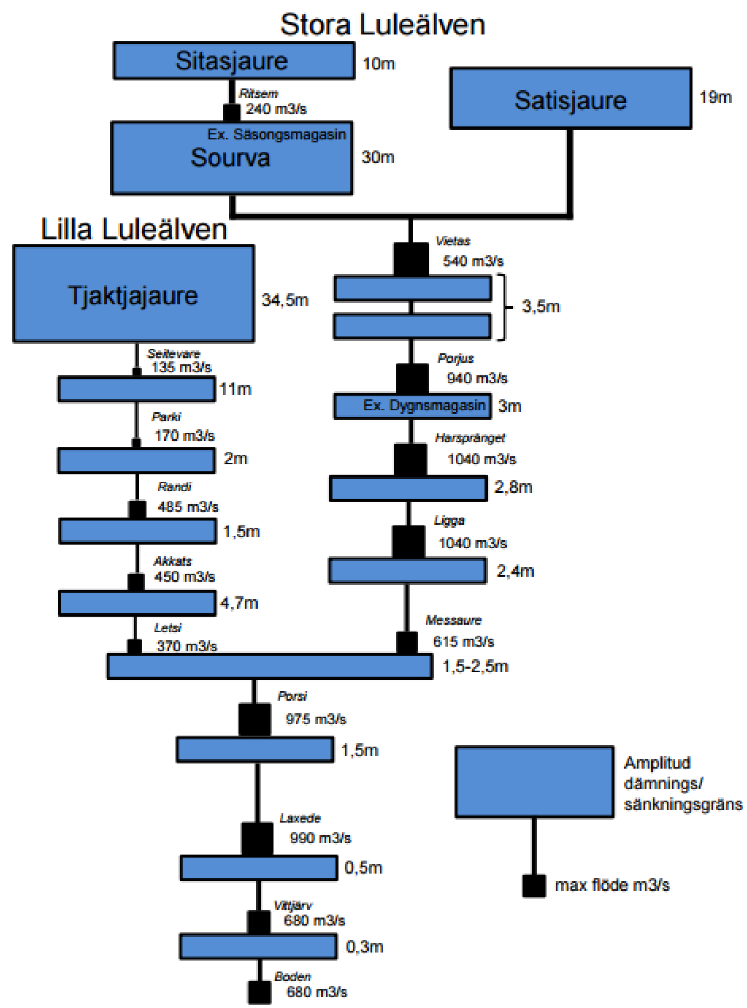
Hydro power modeling

The principles of hydro modeling are simple

- Inflow of water (energy)
- Reservoir constraint
- Turbine constraint
- → Simple intertemporal optimization

The details are tricky

- Environmental restrictions (e.g., minimum flow constraints)
- Cascades
- Icing
- Data requirements and calibration
- → Many additional constraints



How hydro power is modeled in EMMA

- A *stylized* model for research
- An *economic*, rather than engineering, focus
- The purpose is *not* to replace detailed models to be used in project assessment, operational planning, or trading
- A flexible tool that can determine the long-term cost minimum, while representing the most important technical constraints – but only the most important ones
- Model dispatch of hydro plants and investment in hydro plants

"Upper bound" assumptions for flexibility

- Hydro power is modeled very flexibly – real-world dispatch is more constraint
- This implies: estimates for the benefits for wind value are the upper bound

How hydro power is modeled in EMMA

Aggregate technologies

- EMMA aggregates all plants of one technology
- Same for hydro power: one single plant per country

Five core equations to model hydro reservoir power

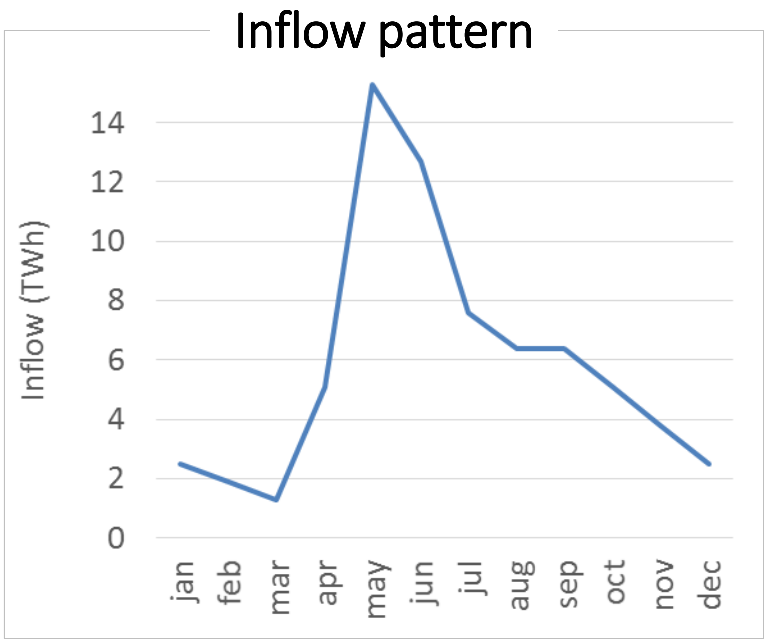
- capacity = existing capacity + new investments – disinvestments
- generation $\leq$ capacity
- $reservoir_t = reservoir_{t-1} + inflow - generation - spillage$
- reservoir $\leq$ reservoir_capacity
- generation $\geq$ min_generation

Pump hydro storage and run-off river are modeled separately

How hydro power is modeled in EMMA

Crucial parameters

- Initial condition: reservoir filled to 70% by beginning and end of year
- Reservoir size: turbine capacity times 2500 hours (“3.5 months storage”)
- Seasonal inflow pattern derived from Swedish statistics
- Minimal generation: 20% - calibrated to minimal Swedish monthly generation (June 2004)



Regional coverage

Existing hydro reservoir capacity in Sweden

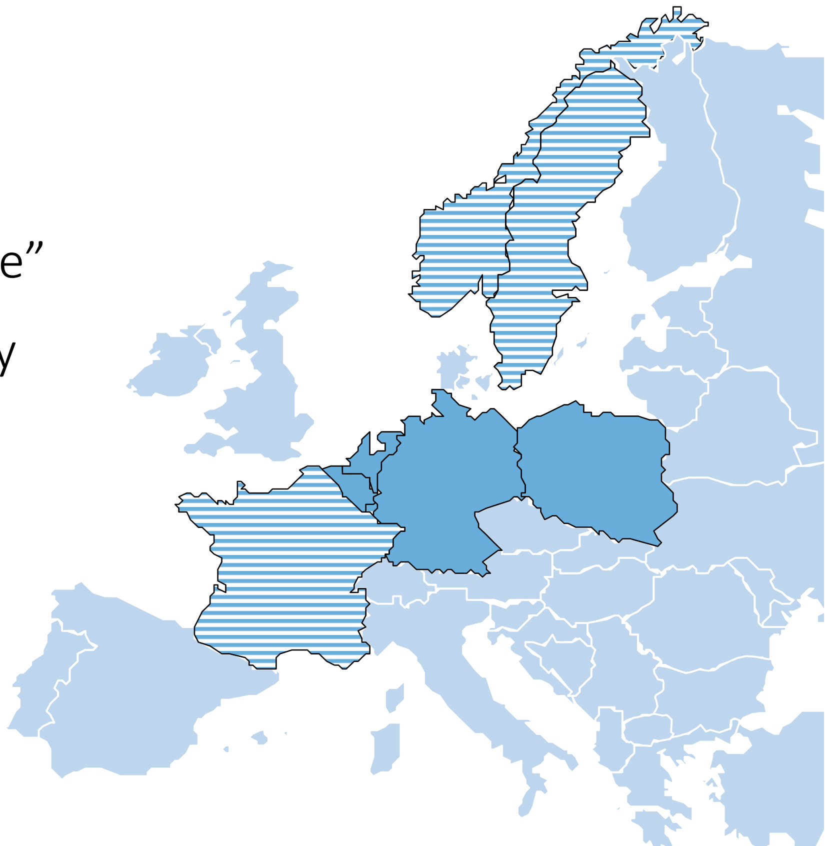
- 16.2 GW – but historical peak generation was 13.7 GW → used as capacity
- 34 TWh storage → "2500 hours of storage"
- 67 TWh inflow → 5000 FLH (60% capacity factor)

Other existing hydro reservoir capacity

- Norway: 25.0 GW turbine capacity
- France: 9.2 GW turbine capacity

Existing pumped hydro capacity

- 6.8 GW in Germany + Luxemburg
- 4.2 GW in France



Hydro parameters

	Run off the river		Pumped hydro storage	Reservoir hydro power	
	capacity	generation	capacity	capacity	generation
Sweden	-	-	-	13.7 GW	67 TWh
Norway	-	-	-	25.0 GW	123 TWh
France	12 GW	34 TWh	4.2 GW	9.2 GW	11 TWh
Germany	4 GW	20 TWh	6.8 GW	-	-
NLD, BEL, POL	< 1 GW	< 1 TWh	-	-	-

Source: Eurelectric PowerStatistics, national statistics. German PHS includes Luxemburg. Swedish and Norwegian reservoir capacity is adjusted to reflect maximal historical generation, rather than the theoretical installed capacity.

Economic framework and assumptions

- Long-term optimum ("greenfield optimization") – generation capacity is optimized
- Hydro capacity is given (not optimized)
- Rational: Hydro sites are limited and are already developed

Tech	Invest (€/kW)	Lifetime (a)	Fixed O&M (€/KW*a)	Vari. O&M (€/MWh$_e$)	Fuel cost (€/MWh$_t$)	CO_2 intens. (t/MWh$_t$)	Efficiency (1)
Nuclear	4000	40	40	2	3	0	0.33
Lignite CCS	3500	40	140	2	3	0.05	0.35
Lignite	2200	40	30	1	3	0.45	0.42
Coal	1500	40	25	1	11.5	0.32	0.46
Nat gas-CC	1000	25	12	2	25	0.27	0.60
Nat gas-OC	600	25	7	2	50	0.27	0.45
Shedding	0	1	0	0	1000	0	1
Wind	1300	20	25				1
Solar	1600	20	15				1
PHS	1500	40	15				0.70
Hydro	3000	40	15				1

Parameter	Value
CO_2 price	20 €/t
Discount rate	7% real

Model features and limitations (and their impact)

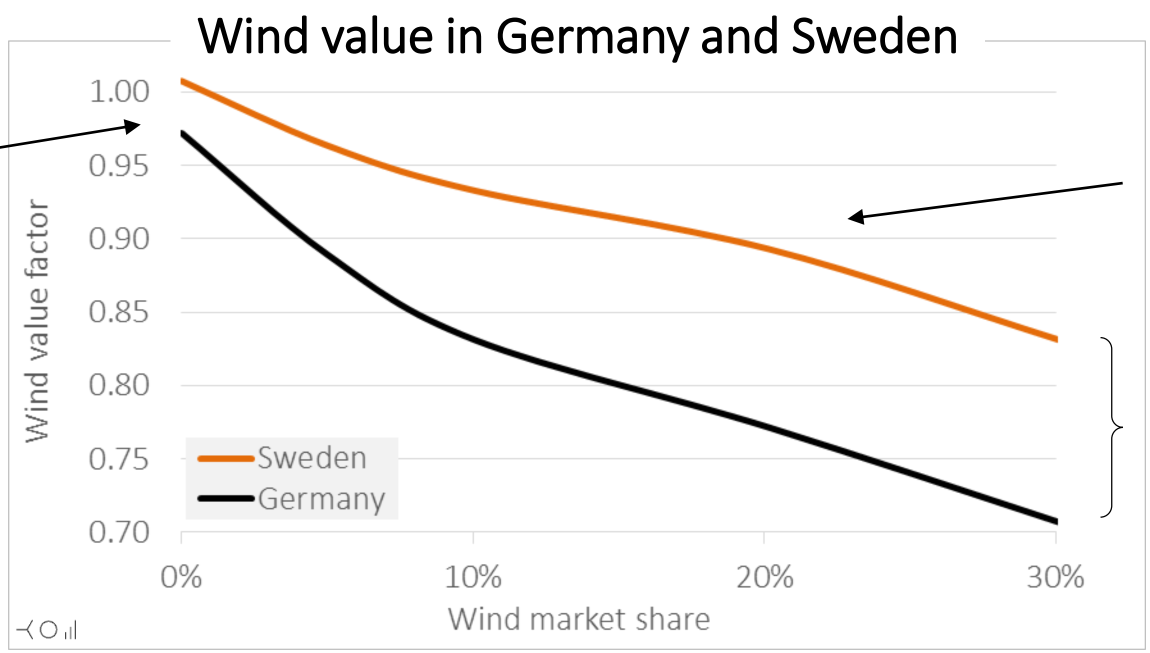
Features modeled	Features not modeled
• High resolution (hourly granularity) • Long-term adjustment of capacity mix • Realistic (historical) wind power, hydro inflow pattern, and load profiles • System service provision • Combined heat and power plants • Hydro reservoirs • Pumped hydro storage • Interconnected power system (imports and exports) • Cost-optimal investment in interconnector capacity • Thermal plant start-up costs • Curtailment of wind power • Balancing power requirements	*Impact likely to be <u>positive</u> (including these features would change value factor upwards)* • Price-elastic electricity demand, e.g. from industry, electrical heating, or e-mobility • Include more countries *Impact likely to be <u>negative</u> (including these features would change value factor downwards)* • Internal transmission constraints (SWE, GER) / bidding areas • More detailed modeling of hydro constraints (cascades, icing, environmental restrictions) • Shorter dispatch intervals (15 min) • Market power of non-wind generators • Ramping constraints of thermal plants • Year-to-year variability of wind and hydro capacity factors, and correlation among these • Business cycles / overinvestments • Imperfect foresight

The impact of the features not modeled (right column) is based on personal assessment.

Market value in the Nordics: EMMA model results

Wind value factor: Sweden vs. Germany

model results



Neon analysis.

Value factor around unity in both countries

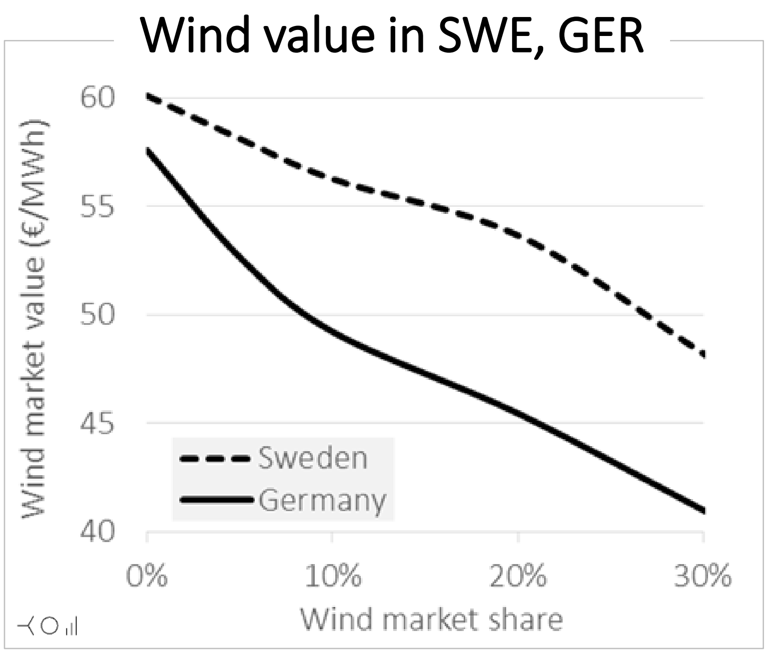
Market value more stable in Sweden

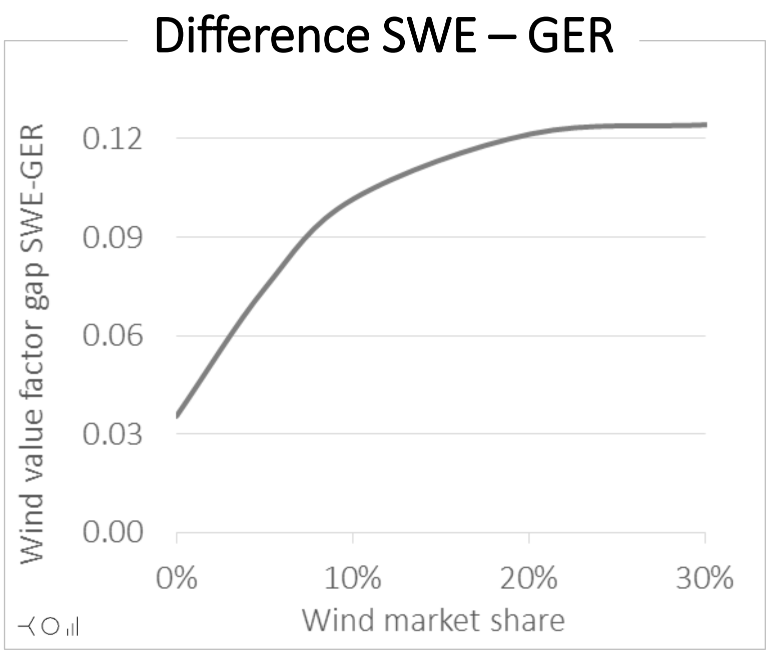
12 points difference at 30% market share (=18% higher value) – recall: upper bound

The market value of wind power drops in both countries, but the drop is less pronounced in Sweden.

30% wind corresponds to ~40 TWh (~ 16 GW) wind power in SWE, ~180 TWh (~90 GW) in GER.

Wind value factor: the Swedish-German gap



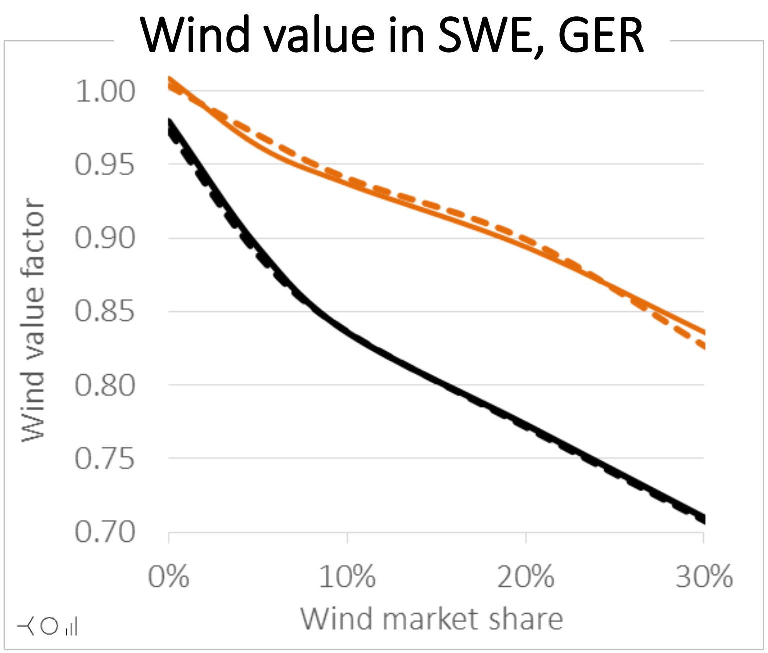


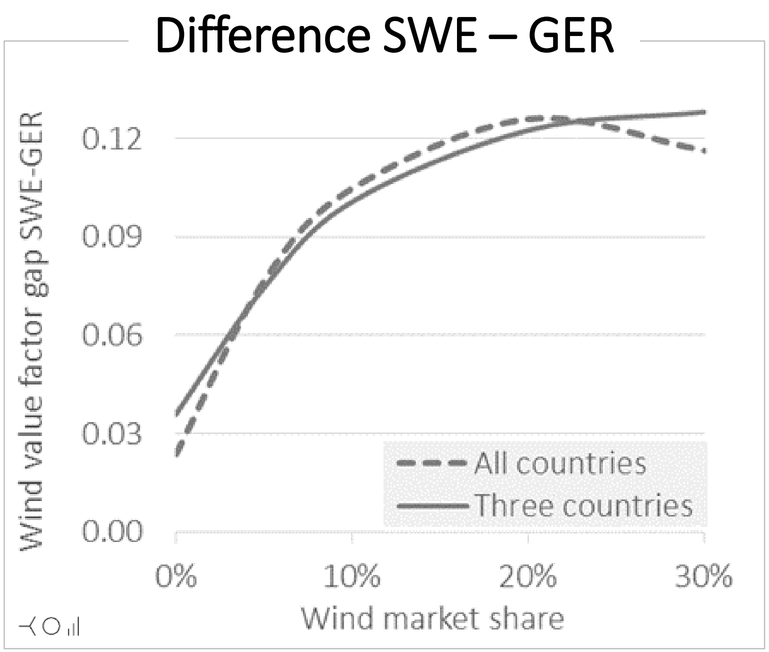
Neon analysis.

Beyond 15-20% market share, the value seems to drop roughly in parallel in both countries.

In other words, beyond 15-20% market share, the value gap between SWE and GER is more or less stable.

Simplification: model three countries



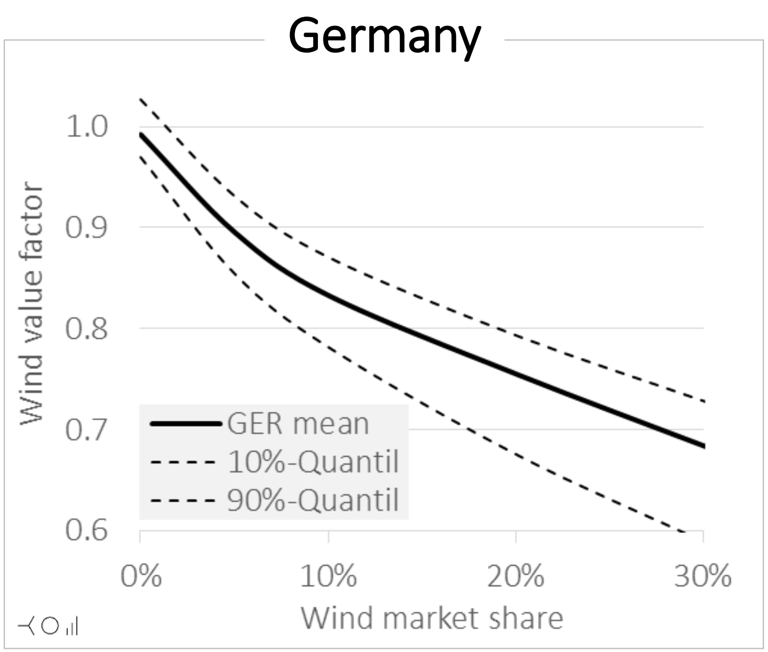


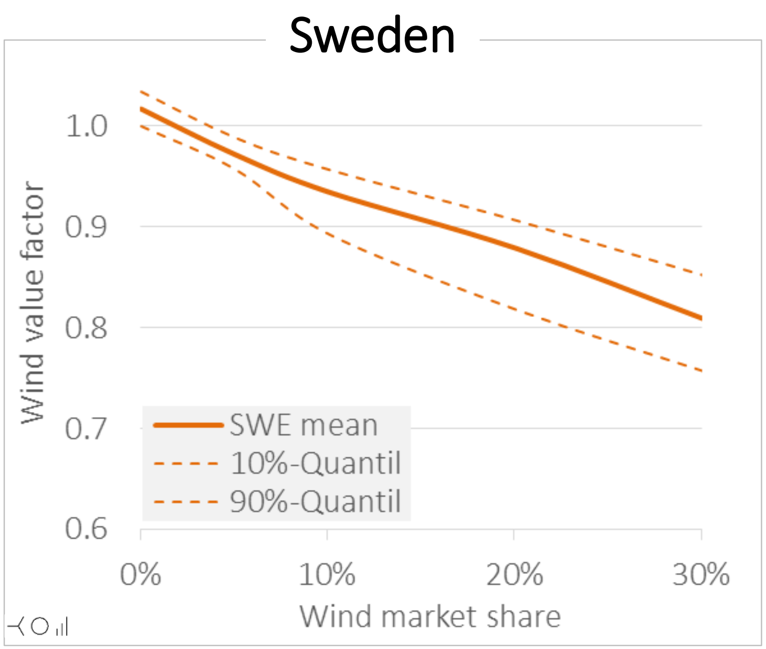
Neon analysis.

Due to numerical constraints, sensitivities are calculated based on a reduced set of countries (SWE, GER, FRA) ...

... the reduced results (dotted lines) turn out to be nearly identical to the full set of countries (bold lines).

Sensitivity analysis: robustness

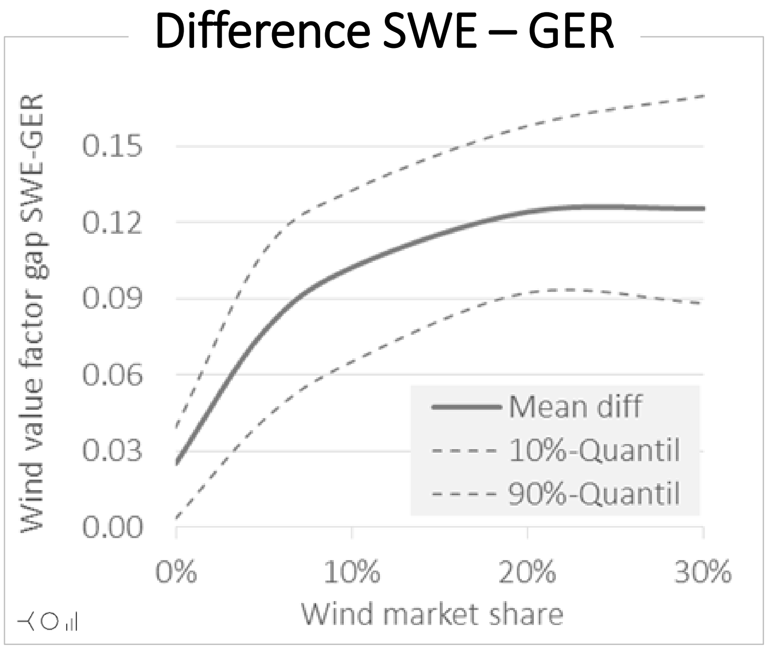




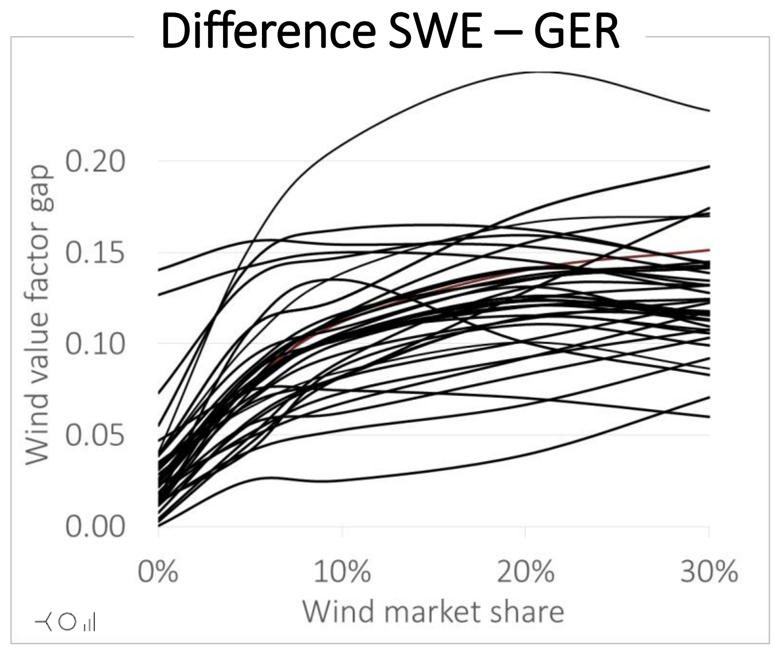
Neon analysis.

67 additional sensitivities: CO_2 price, discount rate, efficiency, fuel pries, investment cost, nuclear policy, interconnection investment, spot price caps, solar penetration, storage capacity, thermal plant flexibility, weather years, low wind-speed turbines. 335 model runs.

Sensitivity analysis: robustness



Neon analysis.

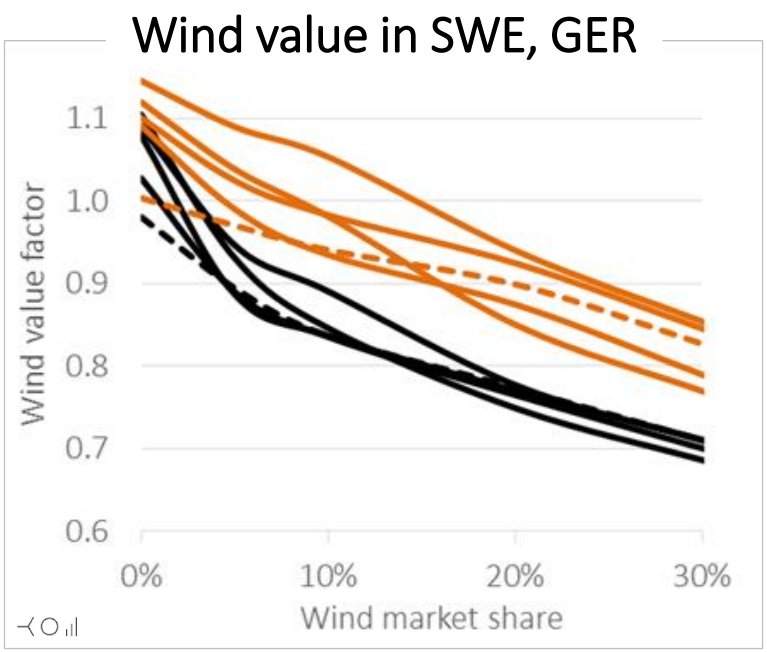


Robust result: wind remains more valuable in Sweden in all sensitivities.

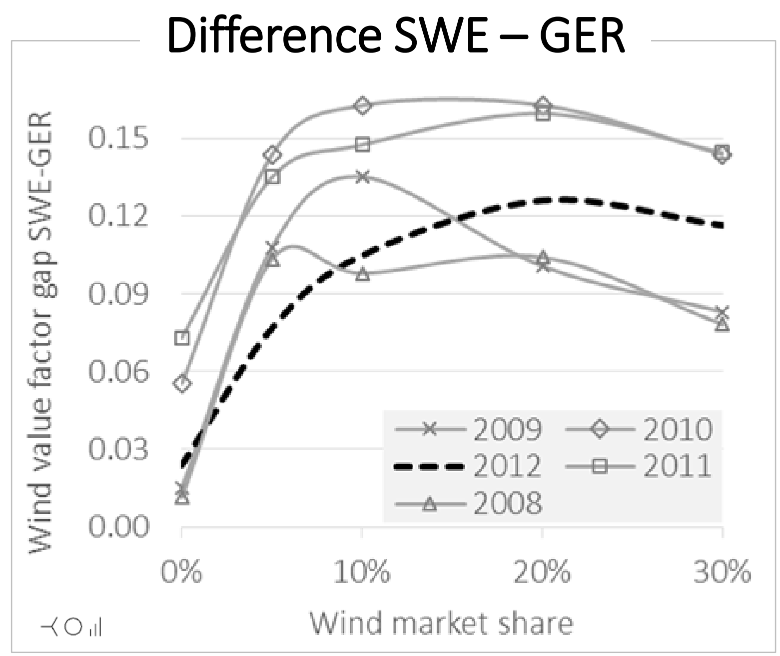
Robust result: wind remains more valuable in Sweden in all sensitivities.

Meteorological years (2008-12)

model results



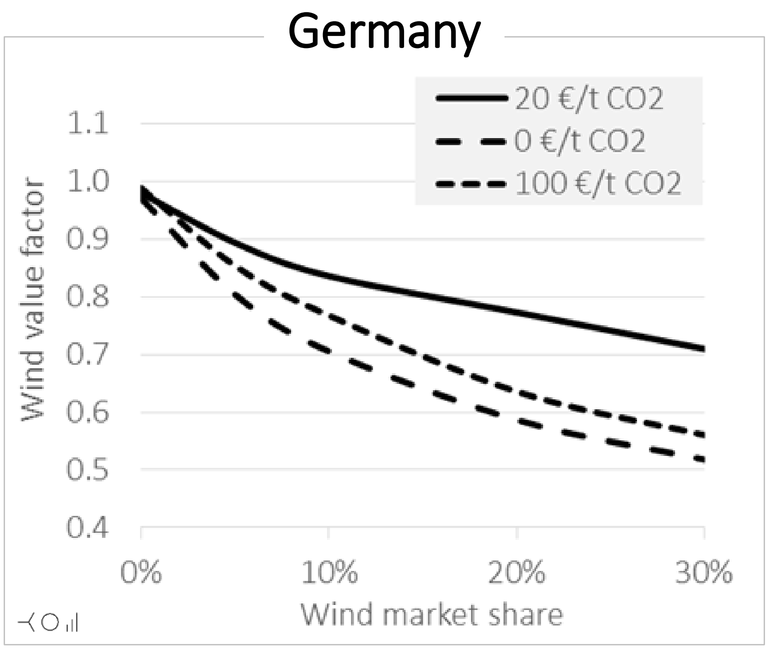
Neon analysis.

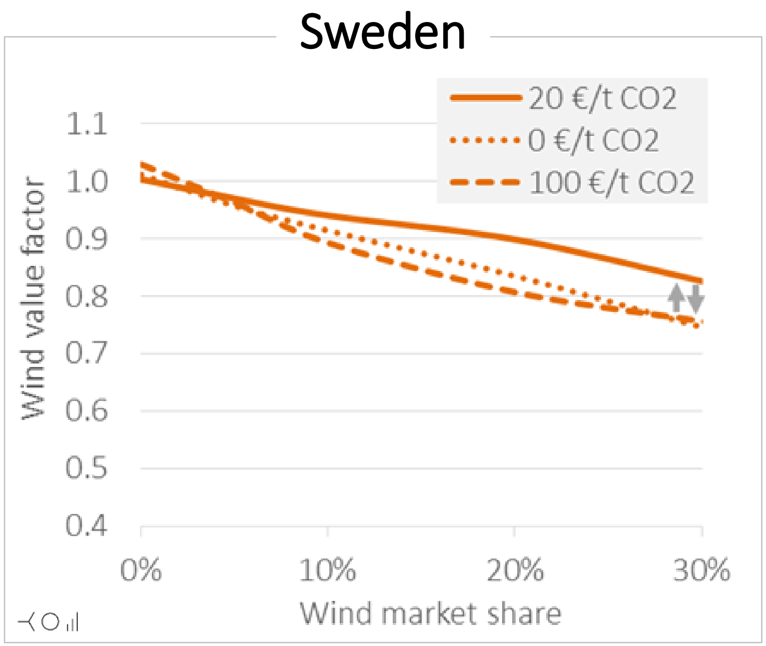


In all five weather years tested, Swedish wind value (orange) is higher than German (black).

In two meteorological years, the value gap is larger than in the benchmark, in two it is lower.

Climate policy





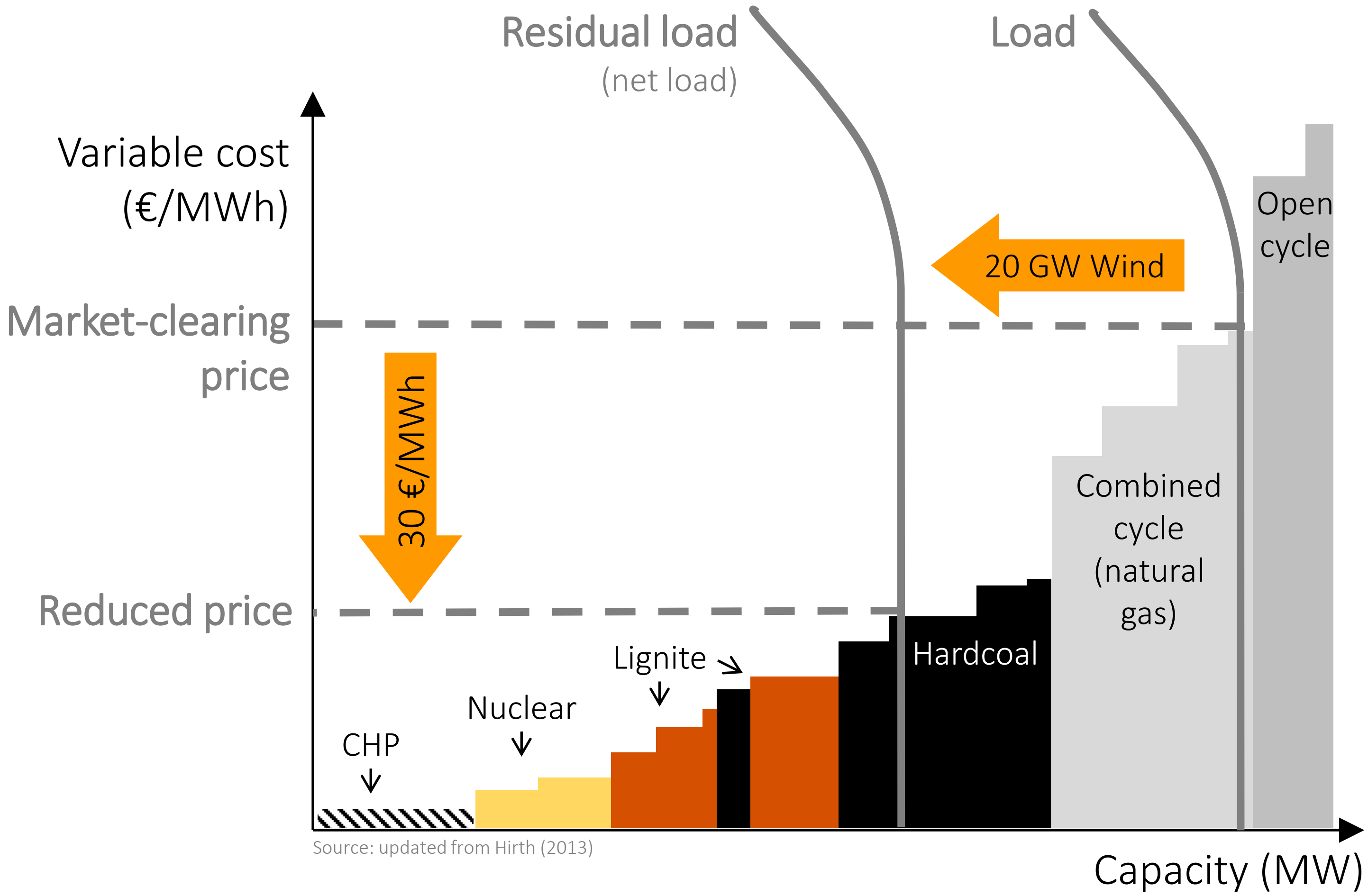
Neon analysis.

Higher carbon prices *reduce* the value of wind power in Germany.

In Sweden, this effect is much less pronounced.

illustrative

The mechanics behind the value drop



Source: updated from Hirth (2013)

Magnitude of the drop:

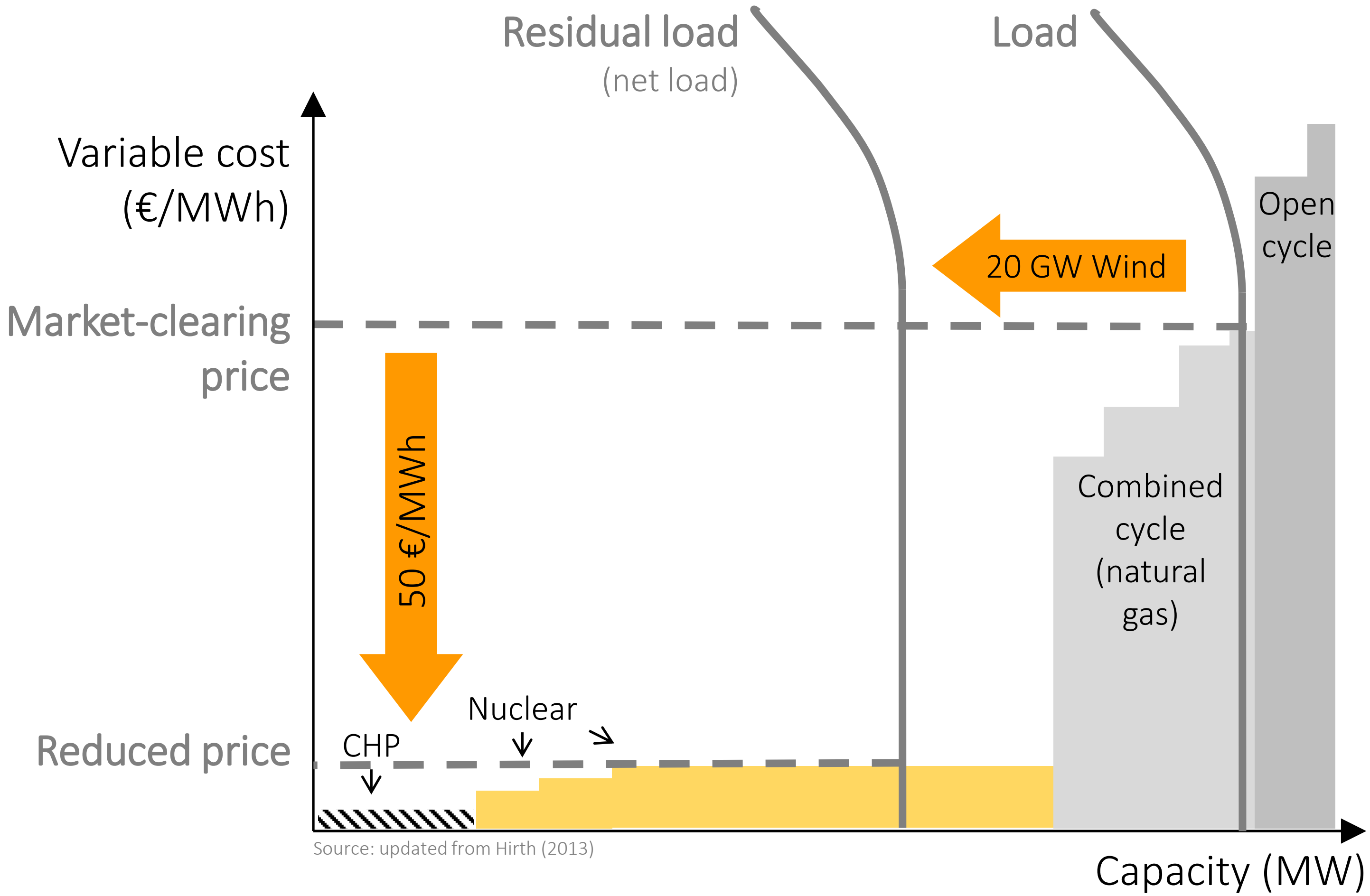
(i) amount of wind generation

(ii) shape of the merit-order curve

(iii) other factors

More base load – larger value drop

illustrative



Source: updated from Hirth (2013)

Magnitude of the drop:

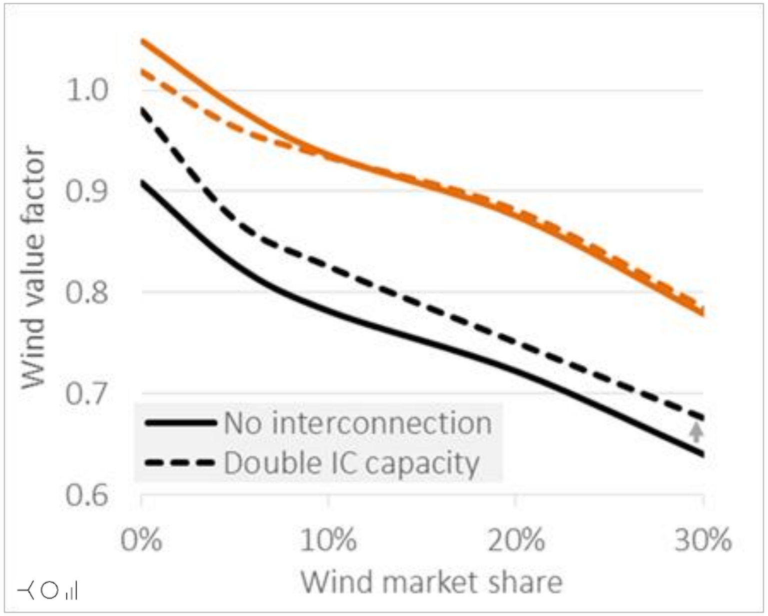
(i) amount of wind generation

(ii) shape of the merit-order curve

(iii) other factors

Interconnection

model results

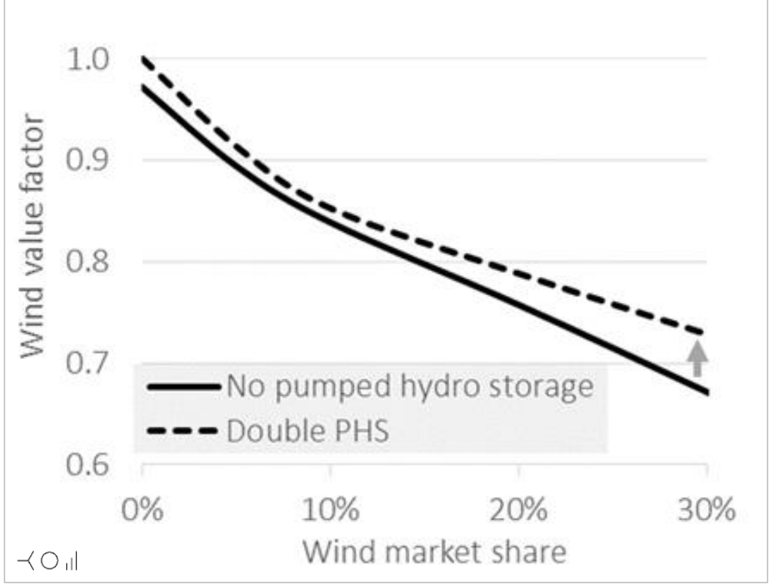


Neon analysis.

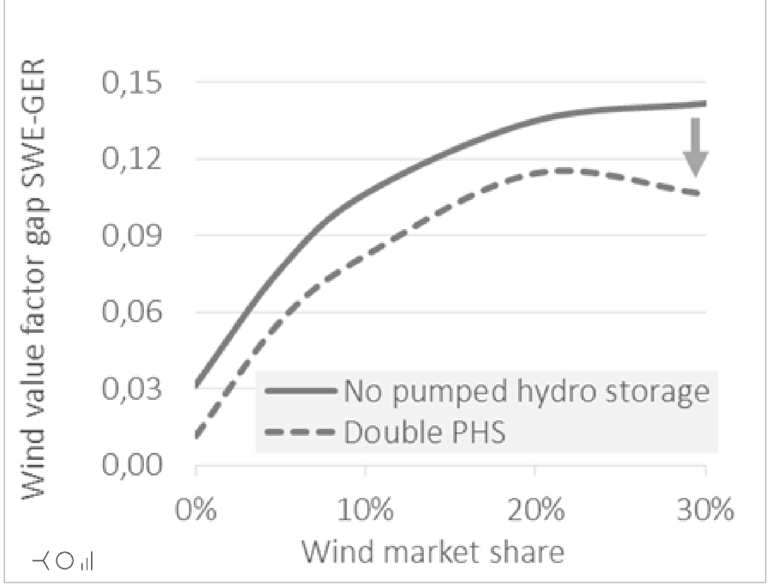
More interconnector capacity has a moderate impact in GER (black) and very little impact in SWE (orange).

Thermal system flexibility

Germany



Difference SWE – GER

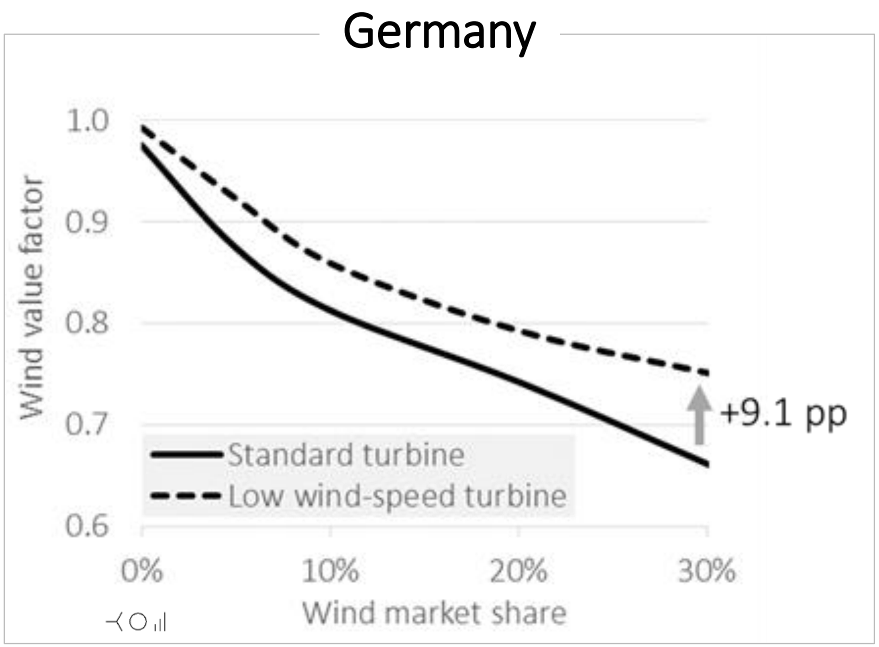


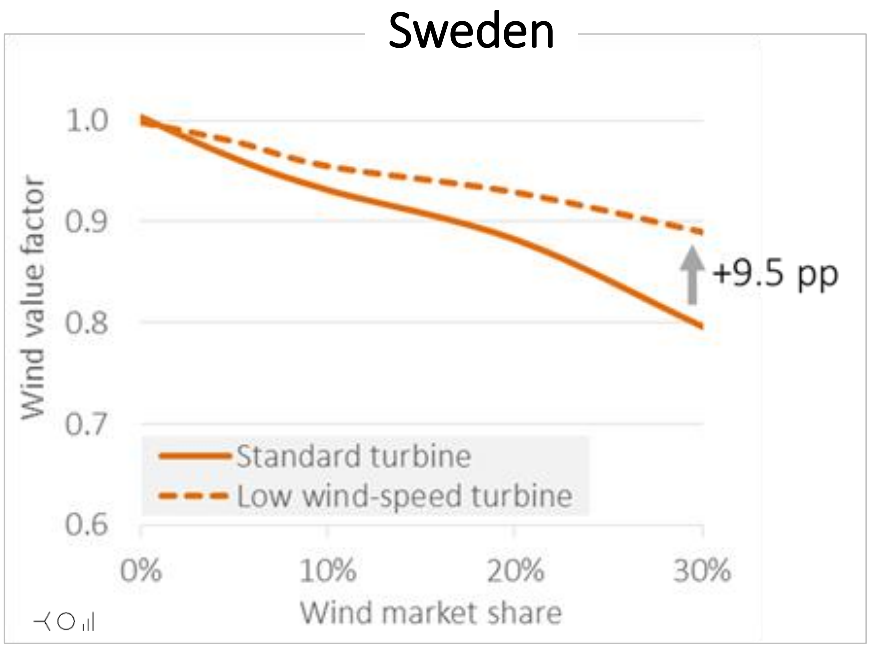
Neon analysis.

Increasing Germany's pumped hydro capacity reduces, as expected, the value gap to Sweden.

model results

System-friendly wind power

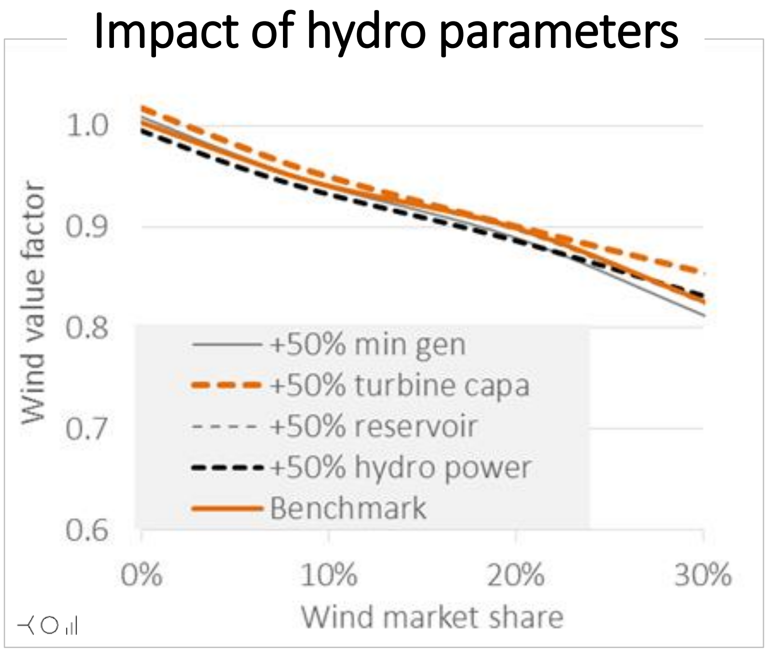




Neon analysis.

Low-wind speed turbines with higher capacity factors increase the market value of wind power (Hirth & Müller 2016). Surprisingly, the benefit of low wind speed turbines is as great in hydro systems as in thermal systems.

Upgrading turbine capacity helps

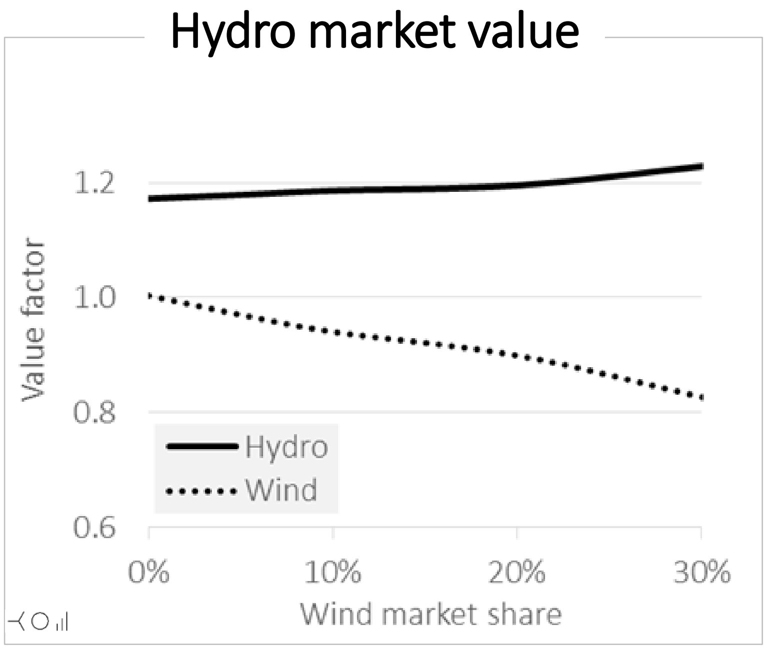


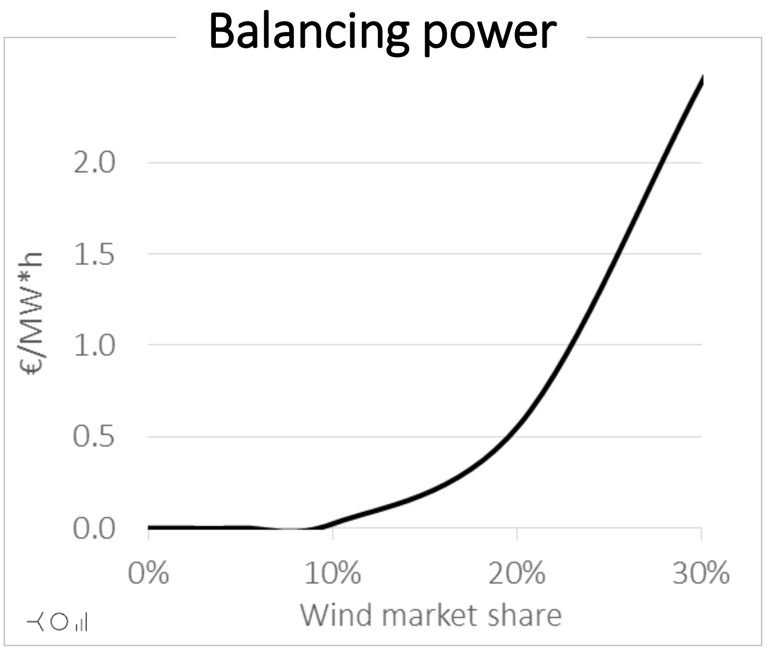
Neon analysis.

Upgrading turbine capacity helps securing the value of wind power.

The market value of *hydro* power

model results



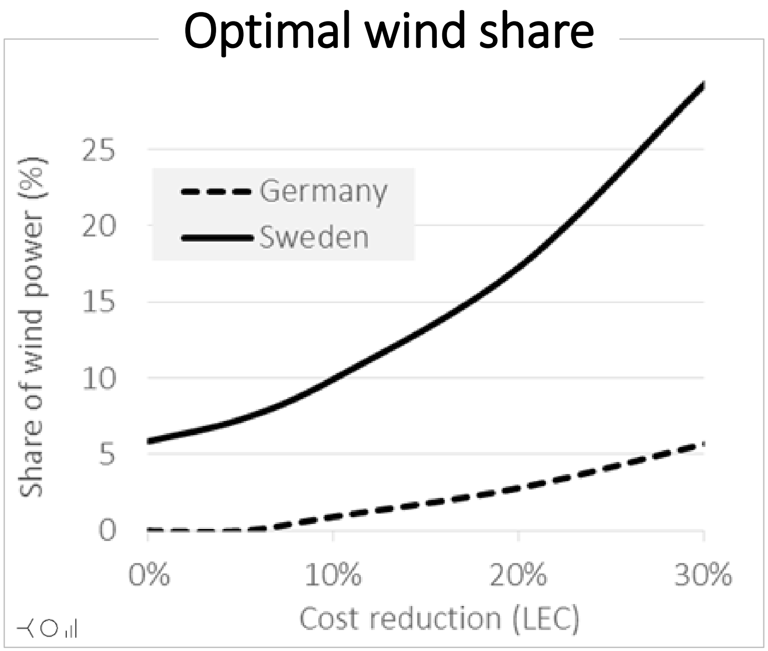


Neon analysis.

The value of flexibility, and hence the market value of hydro power, increases – but only by 4%.

Balancing reserves become more valuable with increasing wind – another upside for hydro power.

The optimal share of wind power



Neon analysis.

The long-term optimal wind power share in energy terms is larger in Sweden, thanks to flexible hydro power.

Conclusions

Conclusions: fundamental remarks

- Market value of wind power drops with penetration
- Higher system flexibility mitigates the value drop
- Hydro reservoirs are an important source of flexibility
- A system with 100% hydro power coming from reservoirs of unlimited sizes would mitigate the value drop entirely
- Value drop is well understood and often quantified in thermal power systems, evidence on hydro systems is scarce
- Nordic hydro flexibility helps securing the wind value in the long-term and a more constant price structure – but the long-living asset structure (hydro, nuclear) leads to lower price levels during the transition
- "System-friendly" in two ways
  - Combining wind power with hydroelectricity
  - In addition: using low-wind speed wind turbines

Conclusions: derived from model results

Based on new model results from EMMA, a stylized model that is likely to overstate the flexibility of hydro power and hence overstate its impact on the market value of wind power.

- The value drop in Sweden is significantly slower than in Germany: moving to 30% market share, the value drops by 30% in Germany but 20% in Sweden
- The value of one MWh of wind power is then 18% higher in Sweden
- Flexibility seems to be “exhausted” around 20% (~30 TWh, 11 GW); beyond that penetration, the value drops in parallel in both countries
- Hydro with low wind speed turbines lead to a very stable value factor of 0.9 – nearly 50% more than classical wind turbines in a thermal system
- The value added of hydro flexibility is larger at high carbon prices
- Hydro power benefits (a little) from more wind power – its value factor increases by 4%; balancing services might provide additional benefits

Market Value Nordic

Hirth, Lion (2016): "The benefits of flexibility: The value of wind energy with hydropower", *Applied Energy* 181, 2010-223, doi: 10.1016/j.apenergy.2016.07.039.

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