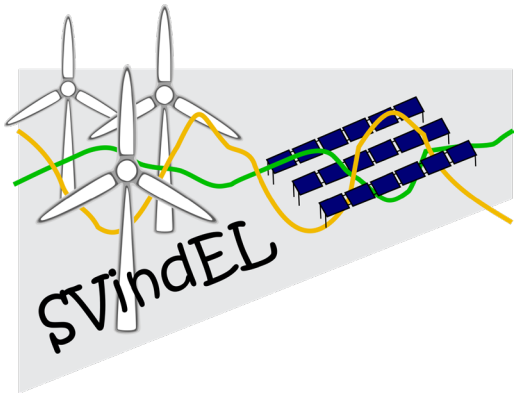
Analysis, Forecasting and Optimization of Utility-Scale Hybrid Wind and Solar Power Parks

David Lingfors



Green Power Summit, 2025-10-13

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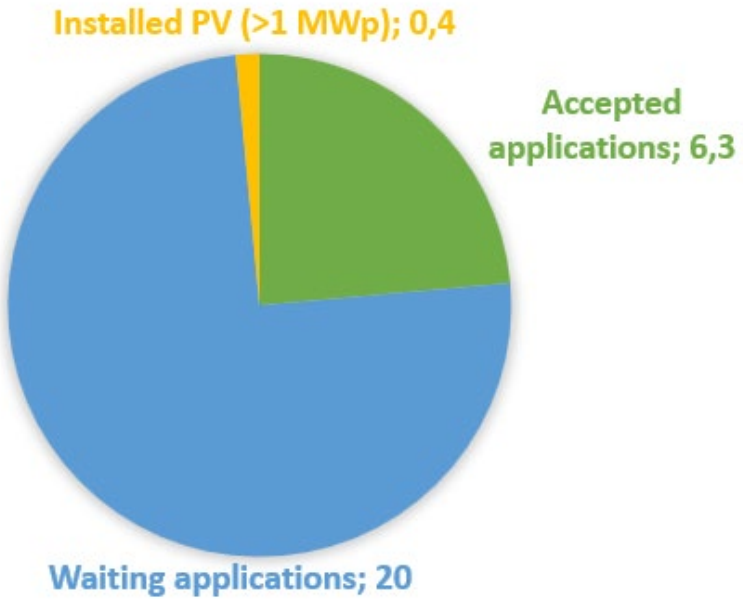
Why Hybrize Wind and PV Parks? (2019)

- *Complementary power production*, *e.g.*, smoother power output.
- *Sharing electrical infrastructure*, *e.g.*, access to grid can be a challenge.
- *Utilization of land*, e.g., property lease.
- *Operation and maintenance work*.

Example of co-located wind and PV park in Sweden [Source: Thomas Carlén].

Why Hybrize Wind and PV Parks? (2025)

- *Complementary power production, e.g.*, smoother power output.
- *Sharing electrical infrastructure, e.g.*, access to grid can be a challenge.
- *Utilization of land*, e.g., property lease.
- *Operation and maintenance work*.
- Booming interest for PV and battery parks
- Low acceptance for new wind power



Status by end of 2024 (TWh)

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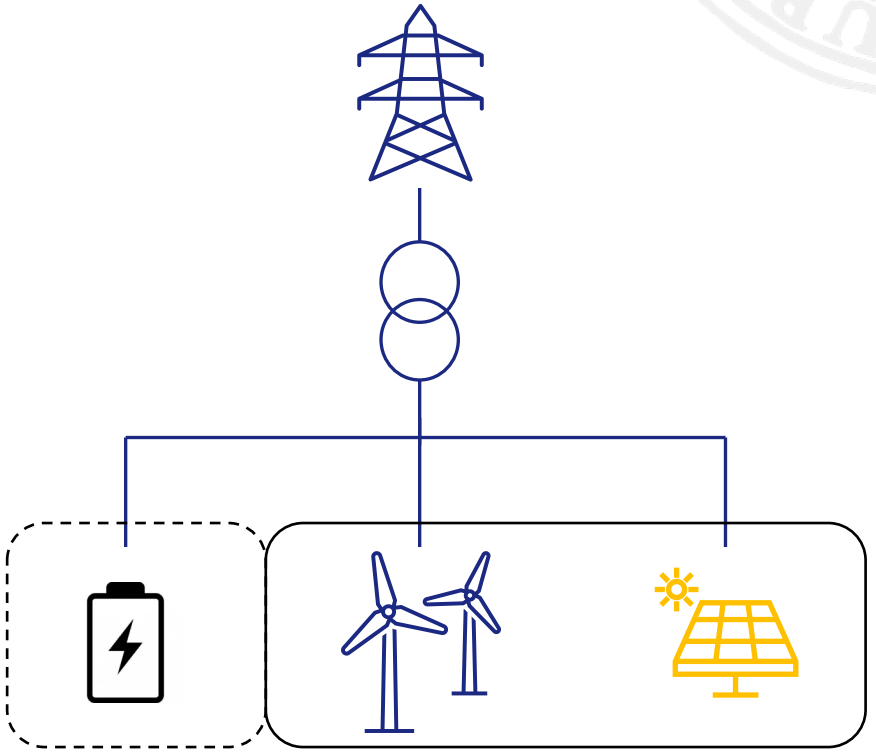
Definition

A hybrid park is located in the same geographical location with a single connection point to the electricity grid.



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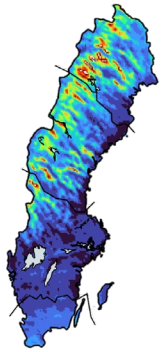
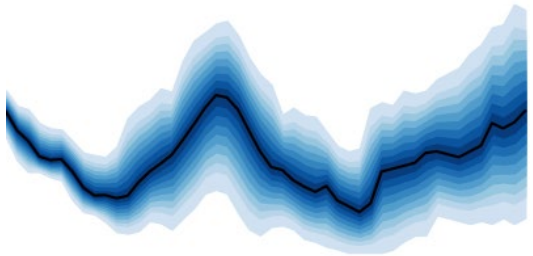
Project aims

1. Review the field of hybrid wind and PV power parks

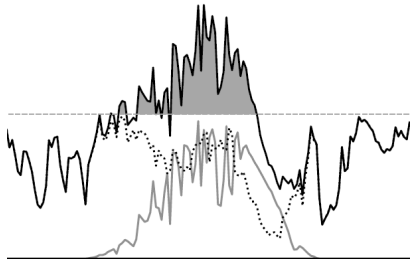
2. Analyze the temporal correlation between wind and PV



3. Quantifying the monetary value of probabilistic forecasts



4. Retrofitting existing wind power parks with PV power parks



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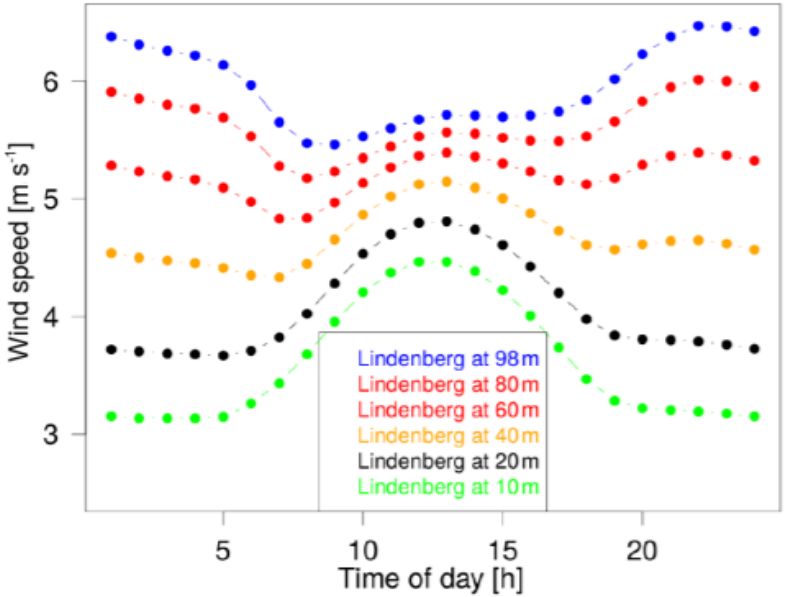
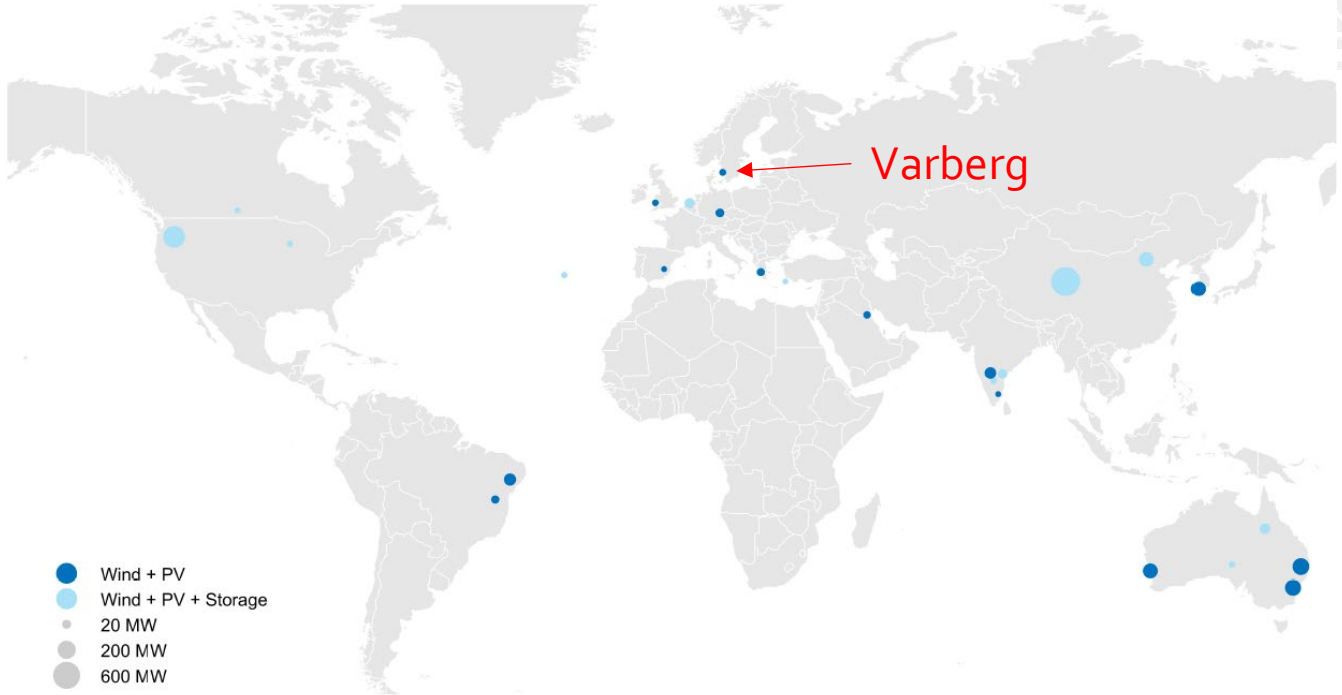
1. Review of the field[1] (2020)

- Few existing hybrid parks
- Only one paper on forecasting aggregated wind and PV power
- Wind and PV experts should collaborate more



Borsche, M. et al. (2016). https://doi.org/10.5194/asr-13-151-2016



[1]Lindberg et al. (2020), https://doi.org/10.1063/5.0056201

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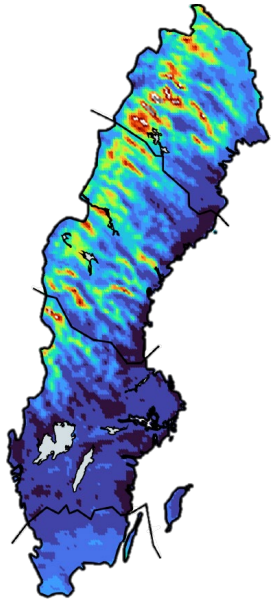
Aim 2: Temporal correlation



How does wind and solar power production correlate across Sweden?

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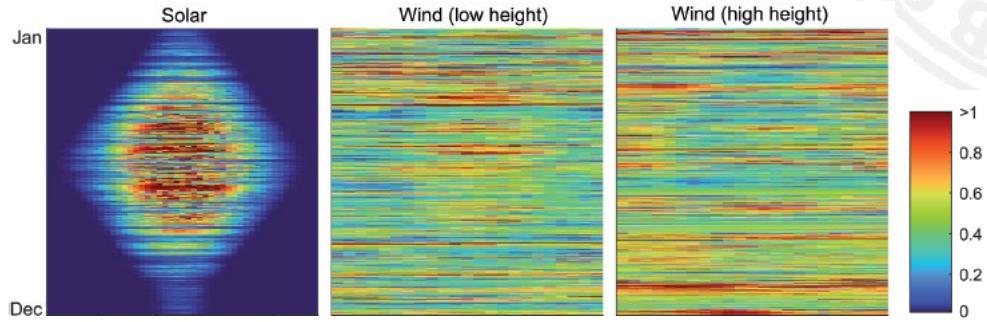
Why analyze correlation?

- Correlation describes how two variables are (linearly) related.

→ If the correlation is negative, we achieve smoothing due to cancellation of variations in each of the signals.

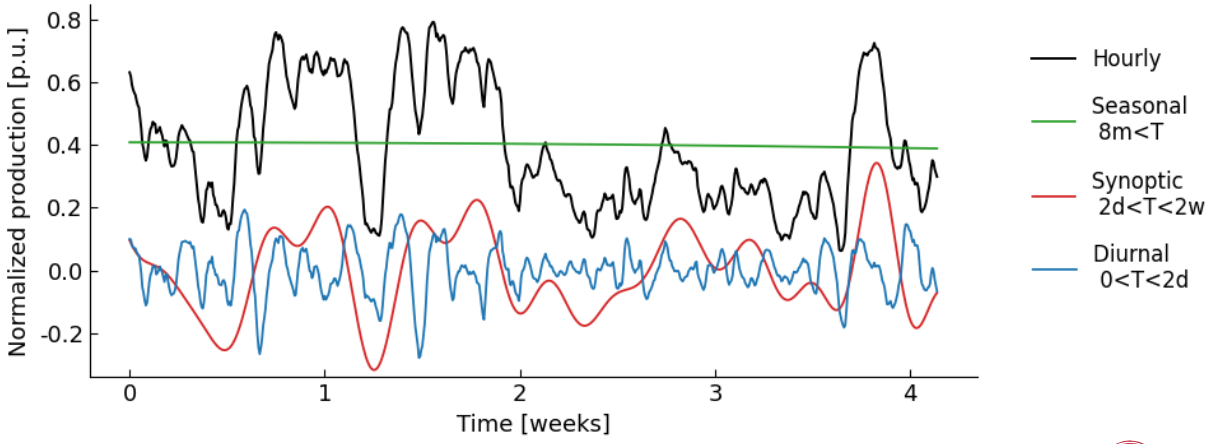
Temporal correlation: Data & Methodology

- Wind and solar power output have different characteristics across different time horizons



Lindberg et al (2021) "Review on power-production modeling of hybrid wind and PV power parks", *J. Renewable Sustainable Energy* 13

- Filtering using fast Fourier transform:
  - Seasonal: longer than 8 months
  - (Midterm: 2 weeks to 8 months)
  - Synoptic: 2 days – 2 weeks
  - Diurnal: less than 2 days



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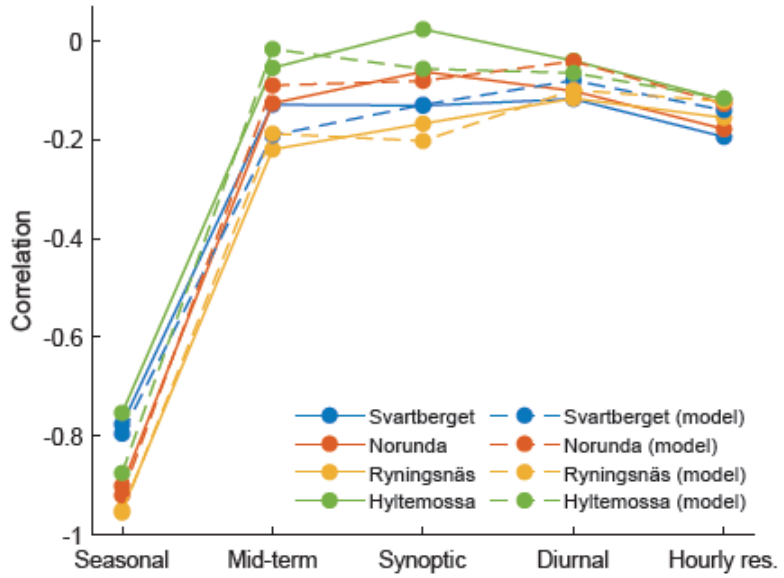
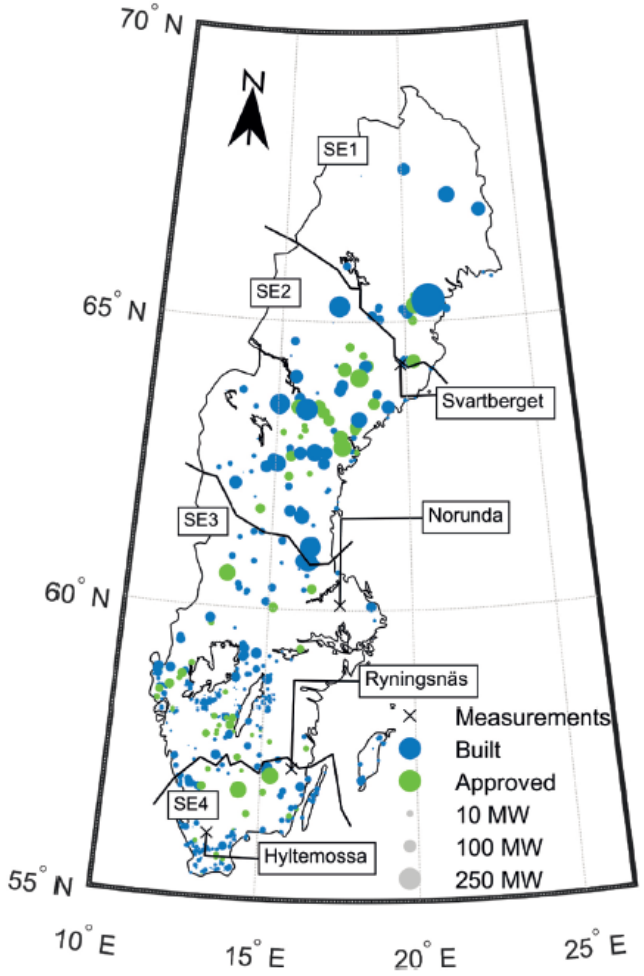
Temporal correlation: Data & Methodology

- Validation of meteorological models against four stations across Sweden
- Wind and solar power production was modeled using meteorological variables from Cosmo-REA6
  - Horizontal resolution of 3x3 km² across Sweden
  - Hourly resolution between January 1995–August 2019





Lindberg et al (2022),
https://doi.org/10.1016/j.energy.2022.124817

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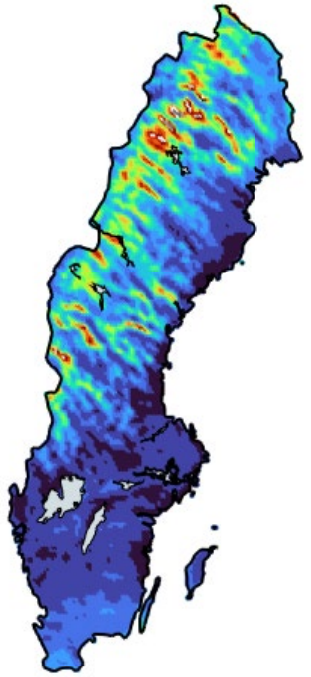
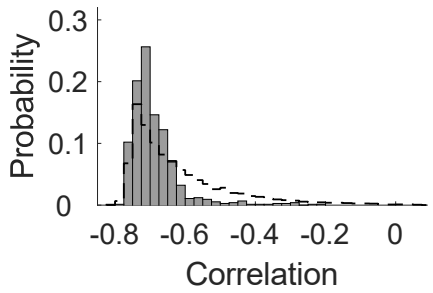
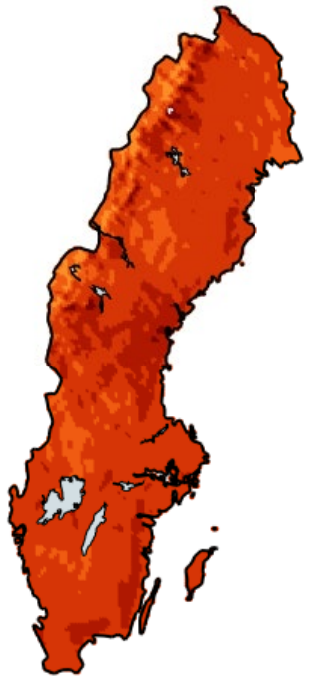
Temporal correlation

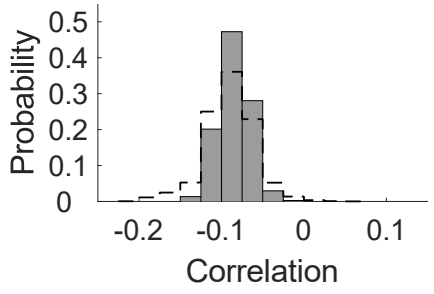
Seasonal



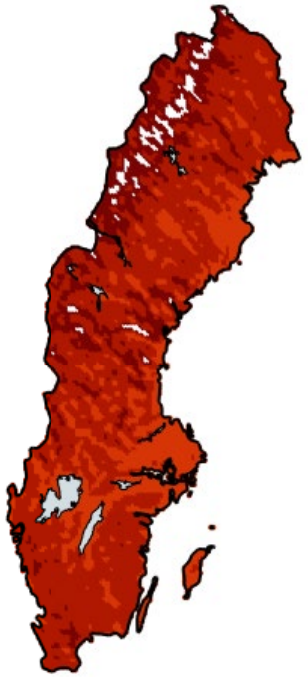


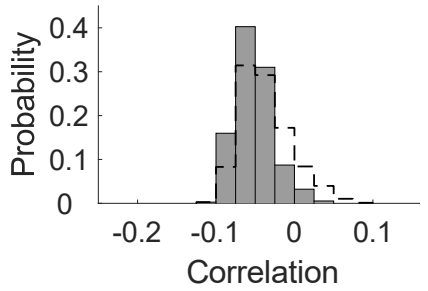
Synoptic

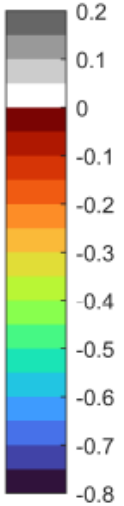




Diurnal







Existing wind farm sites

All sites (3x3 km² grid)

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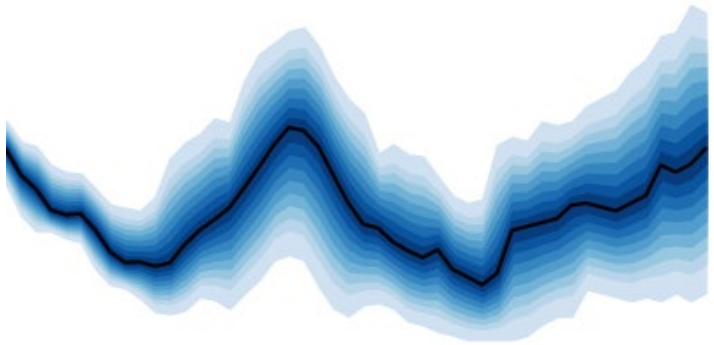
Aim 3: Probabilistic forecasting



Can probabilistic forecasts for the day-ahead market be improved by aggregating wind and solar production?

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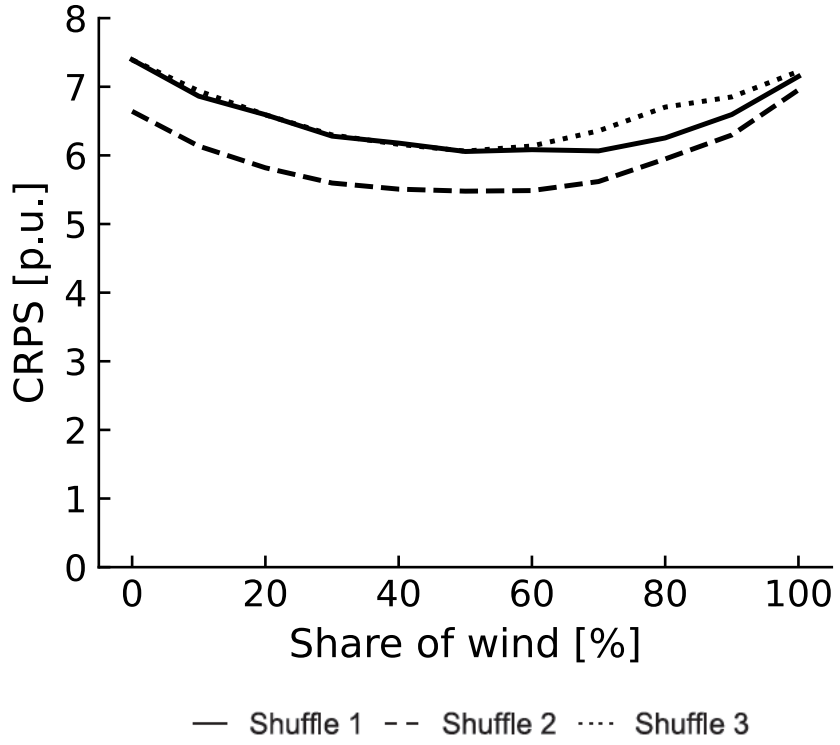
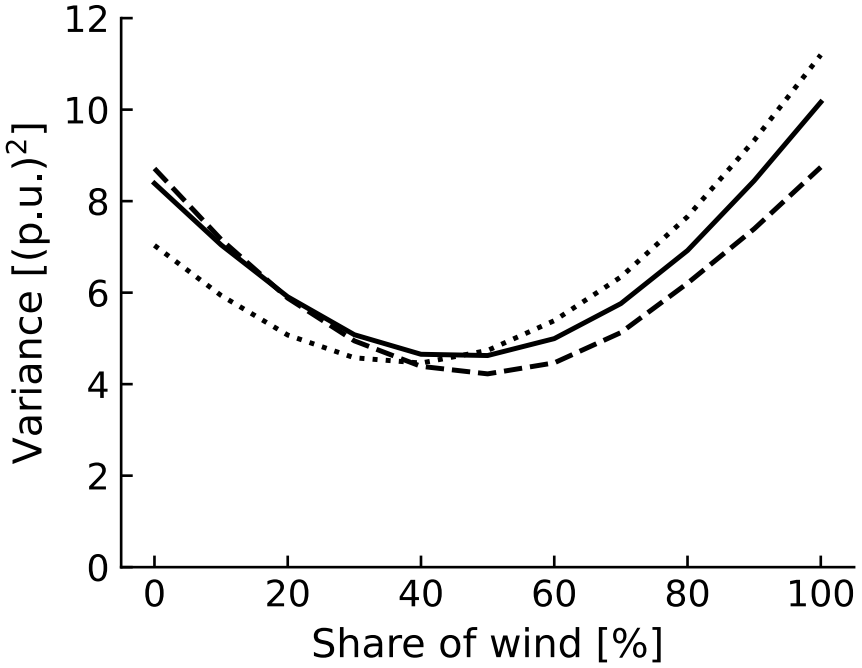
Probabilistic forecasting: Data & Methodology

- Aggregated power production of co-located wind and PV park on the west-coast of Sweden
- Numerical Weather Prediction control ensemble from MetCoOp Ensemble Prediction System (MEPS)
- Weather variables were post-processed using the statistical models Quantile Regression Forest (QRF) + QR.

[Source: Thomas Carlén]

Forecast accuracy





Lindberg et al (2023)
https://doi.org/10.1016/j.adapen.2022.100120

The study also showed that improved forecasts also reduce imbalance costs...

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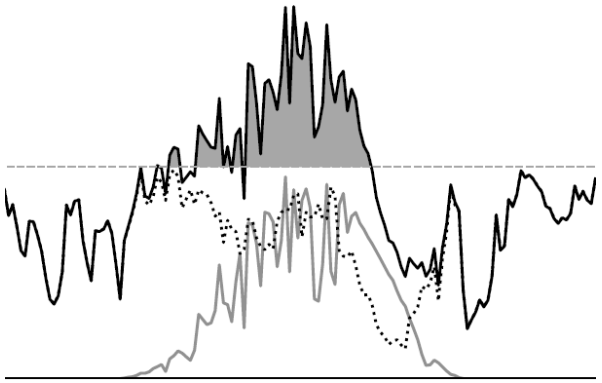
Aim 4: Retrofitting existing wind parks



What determines whether hybridization is feasible or not?

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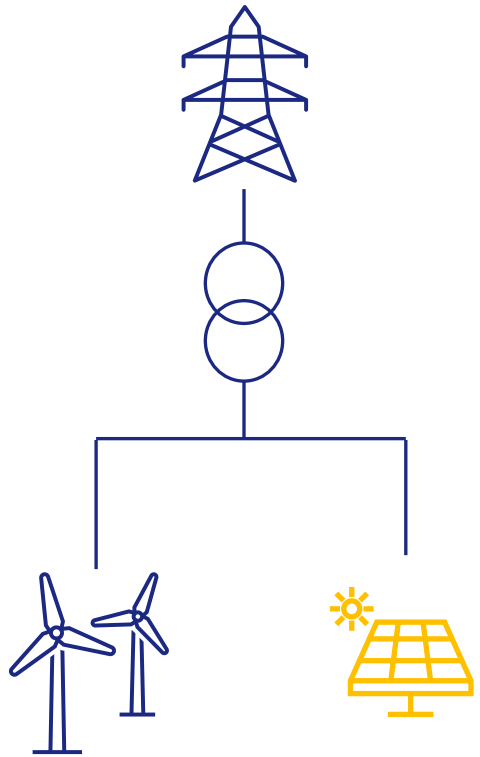
Sharing electrical infrastructure

Retrofitting is done by installing new PV capacity behind the same grid connection point as an existing wind power plant.



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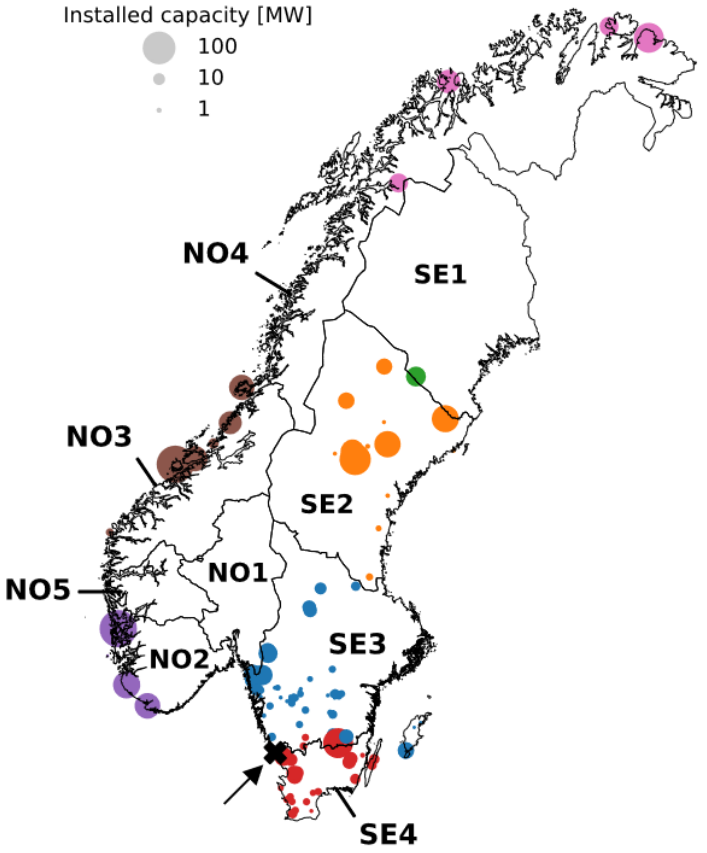
Data

- 5 years of hourly measured power output from 128 wind power parks across Norway and Sweden
- Modeled PV power production at each of the 128 sites
- Simulation model with technical and economical assumptions



The goal is to <u>maximize the net present value (NPV) of the PV park</u>…
…while respecting the capacity in the interconnection point as well as the concurrent wind power production.

Klyve et al. (2025), https://doi.org/10.1016/j.apenergy.2024.124895

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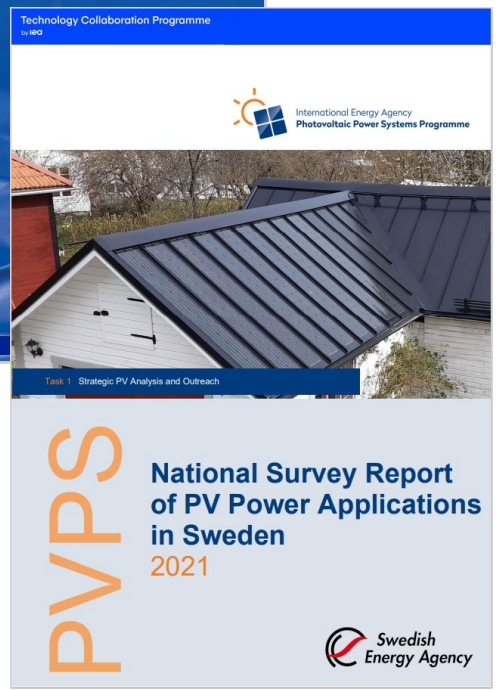
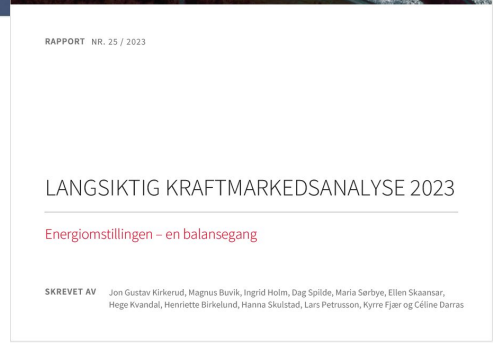
Economical assumptions





Reference scenario	
Lifetime	30 years
WACC	4.5 %
CAPEX	500 kEUR/MW_p
Spot price	45 EUR/MWh
Fixed OPEX	8 kEUR/MW_p/yr
PV degradation	0.2 %/yr

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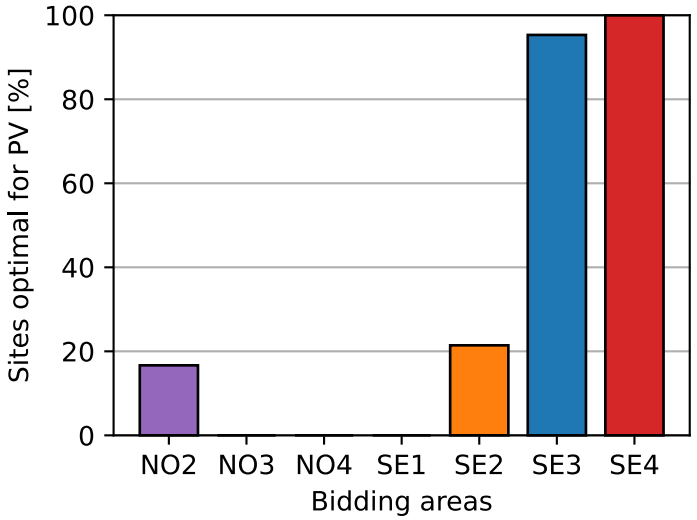

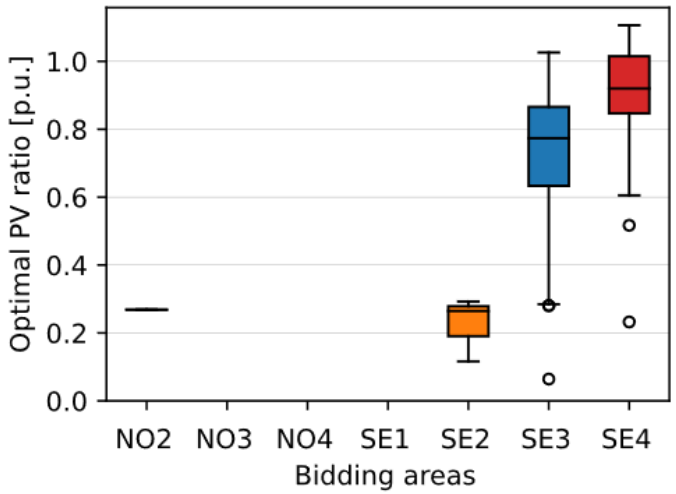

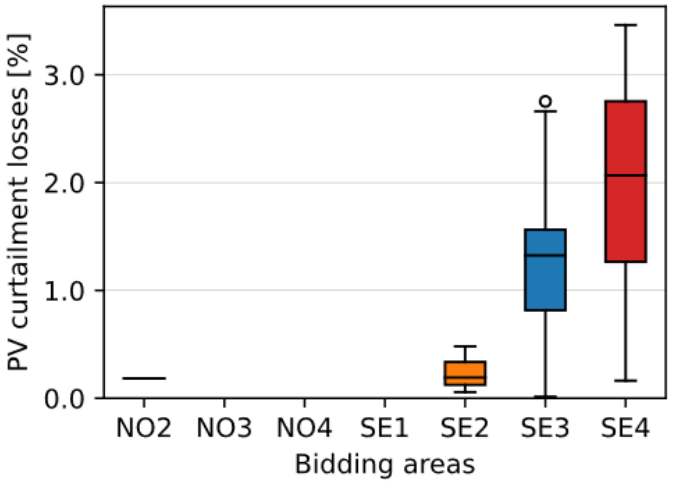

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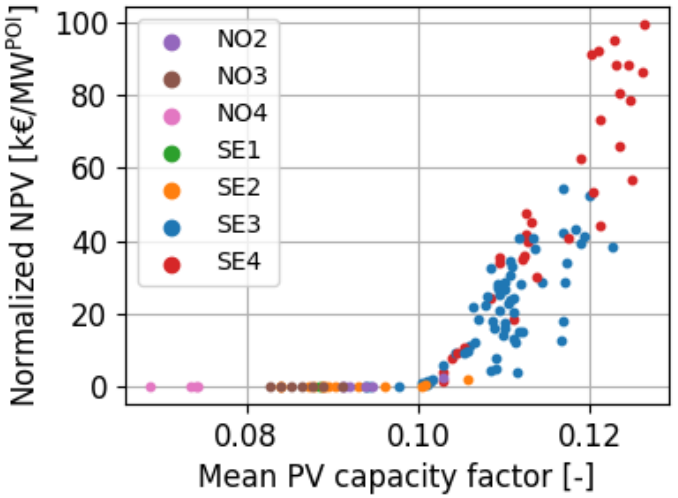

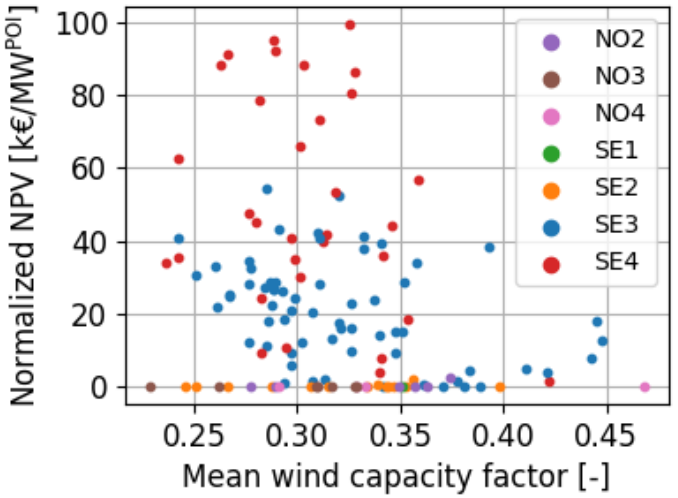

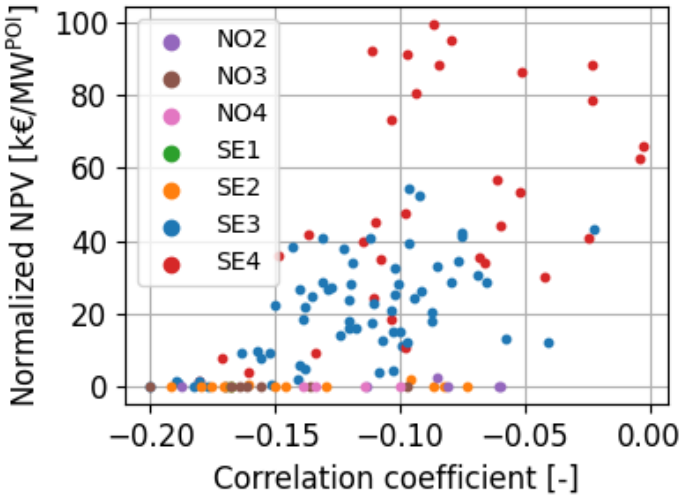

What about the combination of the three?

→ Multiple linear regression

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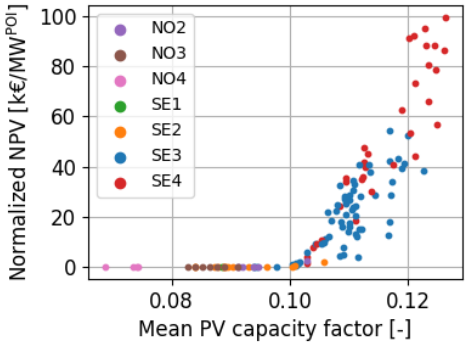

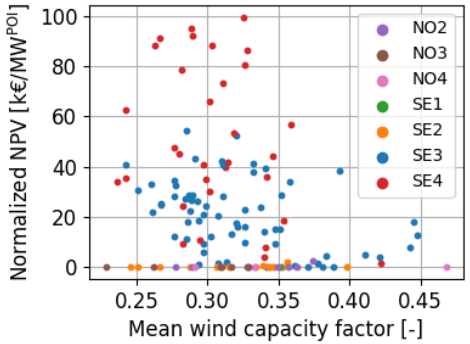

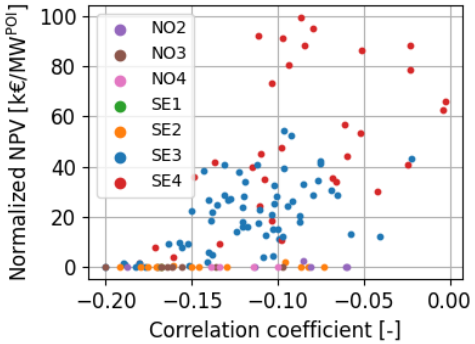

$$NPV = \beta_0 + \beta_1 x_{PV} + \beta_2 x_{wind} + \beta_3 x_{corr}$$

β_0	?
β_1	?
β_2	
β_3	

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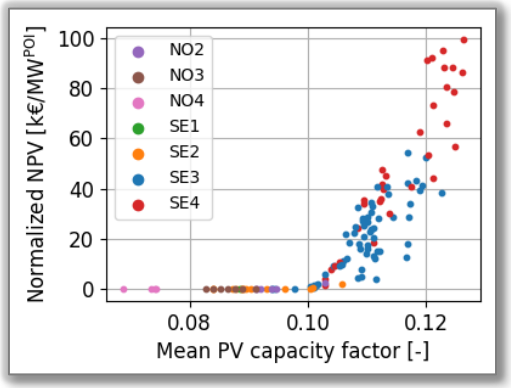
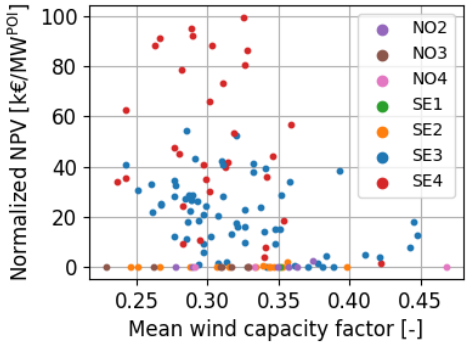
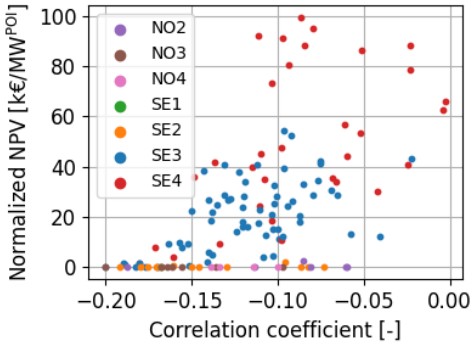


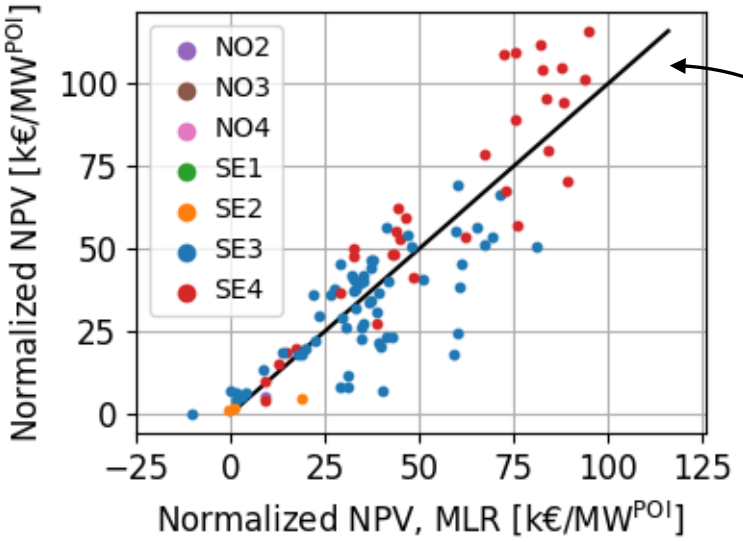




$$NPV = \beta_0 + \beta_1 x_{PV} + \beta_2 x_{wind} + \beta_3 x_{corr}$$

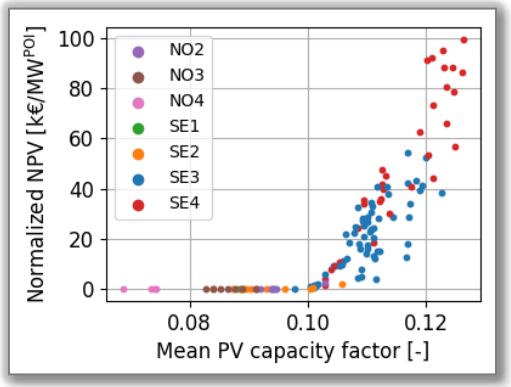
β_0	4.65e4
β_1	2.58e4
β_2	
β_3	

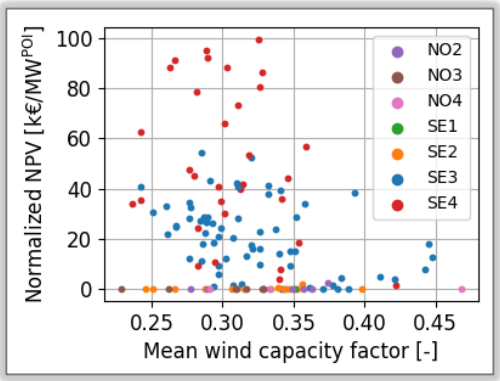
NPV, from simulation model

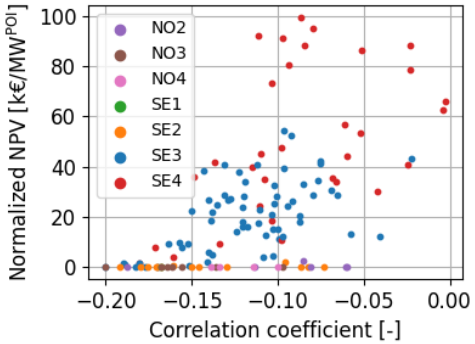


1:1 ratio

NPV, from multiple linear regression and average values



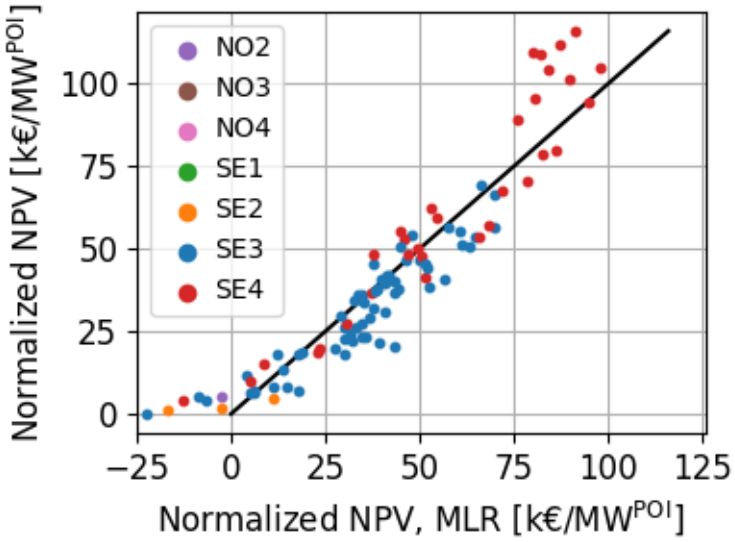




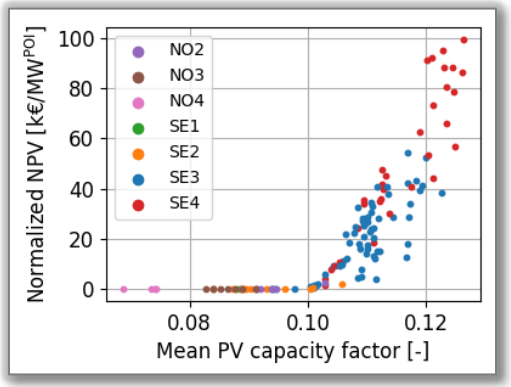
$$NPV = \beta_0 + \beta_1 x_{PV} + \beta_2 x_{wind} + \beta_3 x_{corr}$$

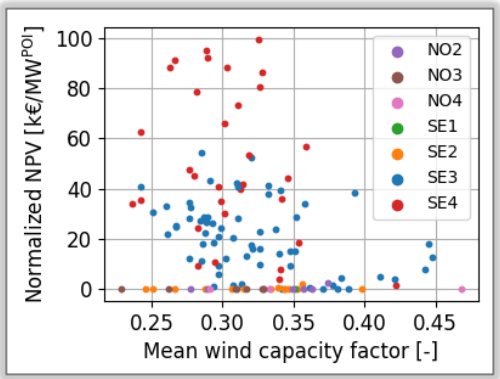
β_0	4.65e4
β_1	2.49e4
β_2	-1.11e4
β_3	

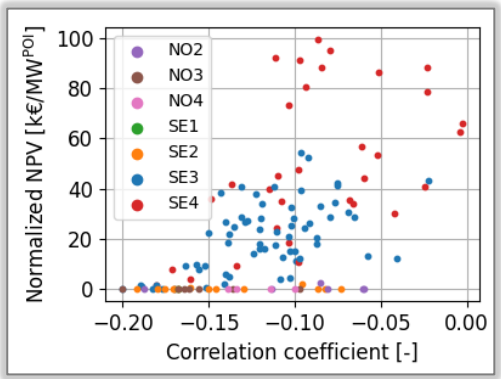
NPV, from simulation model



NPV, from multiple linear regression and average values



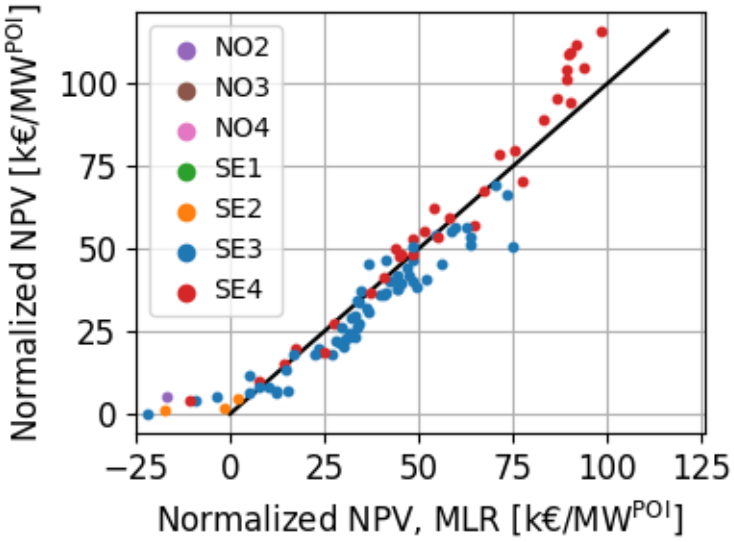




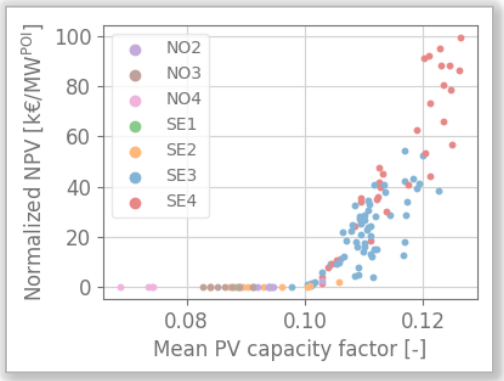
$$NPV = \beta_0 + \beta_1 x_{PV} + \beta_2 x_{wind} + \beta_3 x_{corr}$$

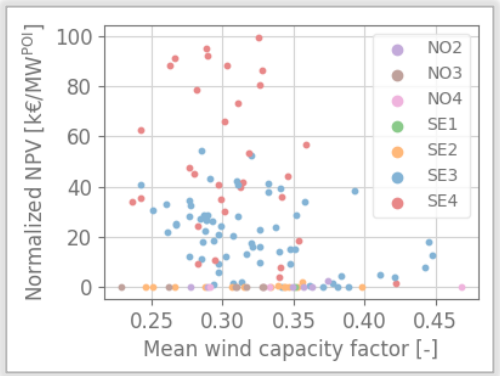
β_0	4.65e4
β_1	2.49e4
β_2	-1.11e4
β_3	-8.86e3

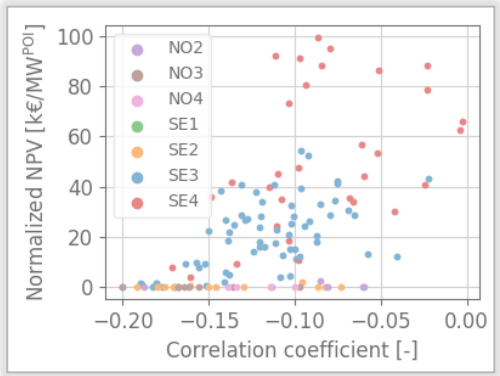
NPV, from simulation model



NPV, from multiple linear regression and average values





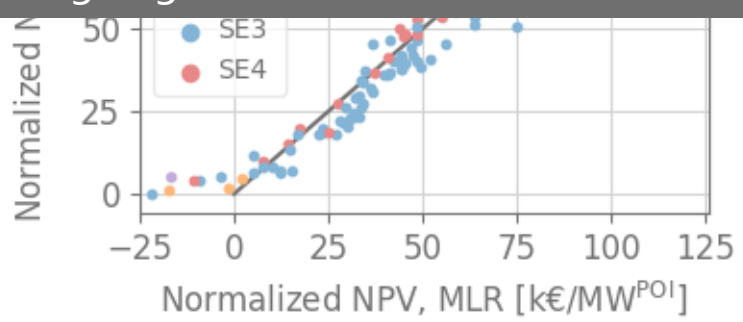


$$NPV = \beta_0 + \beta_1 x_{PV} + \beta_2 x_{wind} + \beta_3 x_{corr}$$

β_0	4.65e4
β_1	2.49e4
β_2	-1.11e4
β_3	-8.86e3

Sites with the highest NPV from retrofitting PV have:
- High PV capacity factors
- Low wind power capacity factors
- Strong negative correlation between wind and PV

NPV, from simulation model

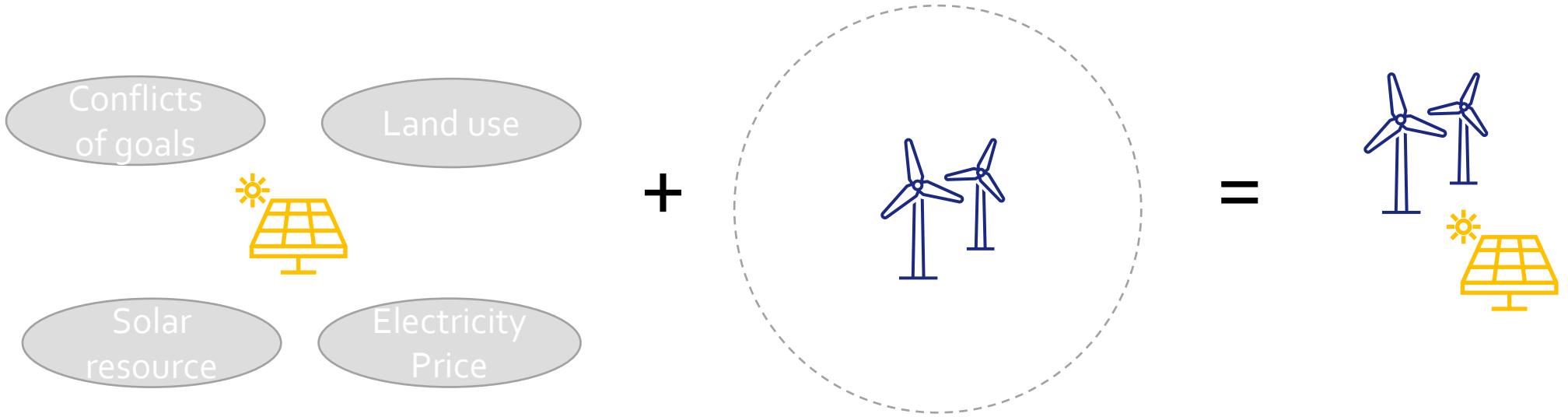


NPV, from multiple linear regression and average values

Next: Suitable land for hybridization

Analyse characteristics of existing PV parks

Compare to conditions near wind sites

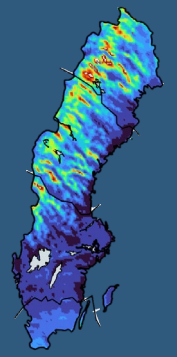


Conclusions

Literature review

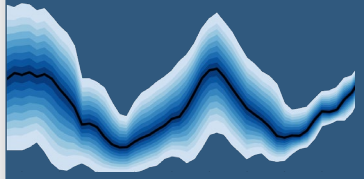
- Large potential for hybrid parks globally
- Research field is immature

Temporal correlation



- Time scales relevant for grid-integration are generally negatively correlated

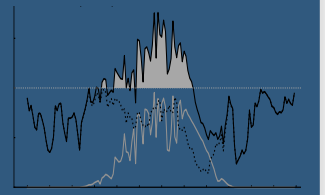
Probabilistic forecasting



- The smoothing effect from co-located wind and solar improve probabilistic forecast accuracy and reduces imbalance costs

Retrofitting existing wind parks

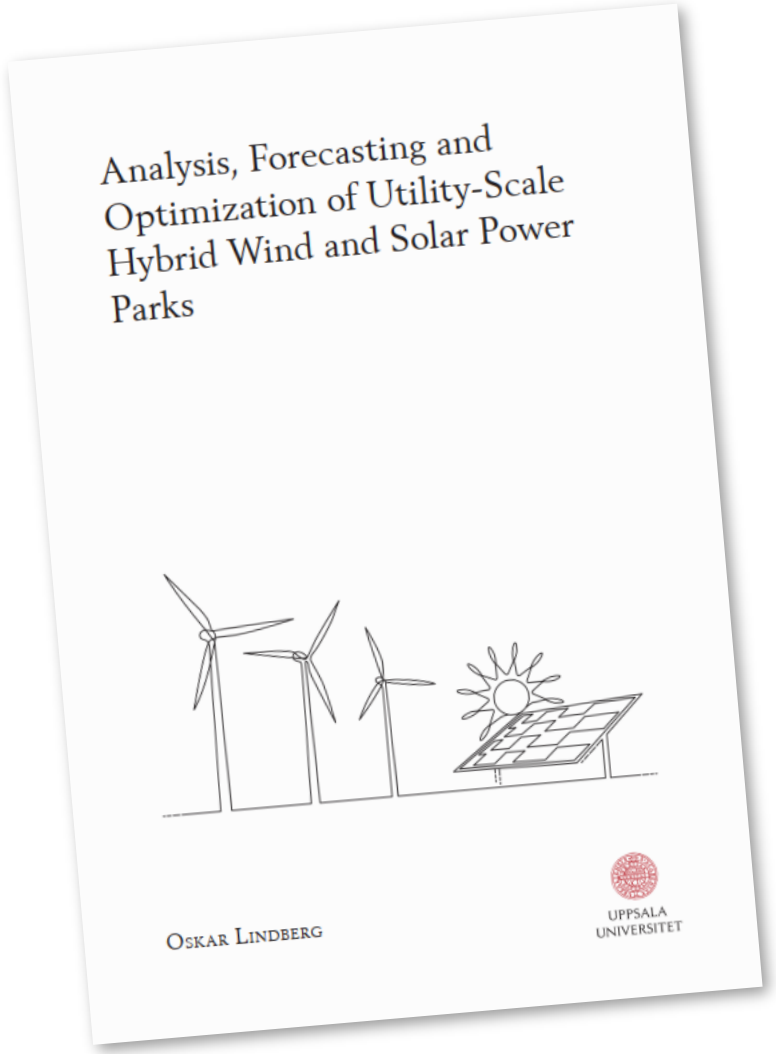
- The best sites to hybridize are the ones with high PV and low yearly wind capacity factors and strong negative correlation.



Role of the County Administrative Board

- Multifunctional authority: Permission processes, physical planning, rural development…
- Foster dialogue between actors in the regional energy system
  - #uppsalaeffekten
- Support municipalities
  - Municipal energy planning
- Strategies and policies
  - Climate and energy strategy
  - Regional roadmap for electrification

LÄNSSTYRELSEN
UPPSALA LÄN



Oskar Lindberg's thesis is available here!
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Thank you for your attention!

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