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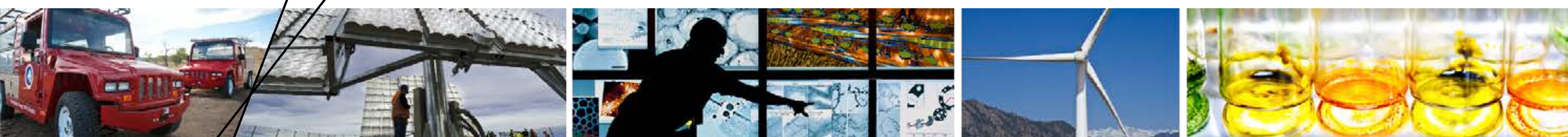
Analysis of Variability and Uncertainty in Wind Power Forecasting: An International Comparison



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Wind Power Forecasting

- One of the critical challenges of wind power integration is the variable and uncertain nature of the resource.
- Short-term forecasting of wind power generation is uniquely helpful for balancing supply and demand in the electric power system, thereby reducing economic costs and reliability risks.
- Wind forecasting models can be broadly divided into two categories: (i) forecasting based on the analysis of historical time series of wind; and (ii) forecasting based on numerical weather prediction (NWP) models.
- It is important to understand the nature of wind power forecast errors, especially for large and infrequent forecast errors that can dramatically impact system costs and reliability.

Research Motivation and Objectives

Motivation

- Understanding forecast errors and uncertainties in different power systems and scenarios is helpful for:
  - Developing improved wind forecasting technologies, and
  - Better allocating resources to compensate for wind forecast errors.

Research Objectives

- Investigate the uncertainty in wind forecasting at different times of year.
- Compare wind forecast errors in different power systems using large-scale wind power prediction data from six countries: the United States, Finland, Spain, Denmark, Norway, and Germany.

Wind Forecasting Scenarios

- Hourly day-ahead wind power forecast errors throughout a year
- Forecast errors at a specific time of day throughout a year
  - Hour 14:00 in this paper
- Forecast errors at peak and off-peak hours of the day
  - Peak hours: 7:00 – 22:00
  - Off-peak hours: 23:00 – 6:00
- Forecast errors during different seasons
  - Summer and winter
- Extreme events: large overforecast or underforecast errors
  - More than 25% of wind forecast errors are normalized by total wind capacity
- Forecast errors when the current wind power generation was at different percentages of the total wind capacity
  - Less than 25% of the total wind capacity
  - Between 25% and 75% of the total wind capacity
  - More than 75% of the total wind capacity

Methodology Development

- Kernel density estimation (KDE): estimates the distribution of wind power forecast errors

$$\hat{f}(x;h) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

  - The Gaussian kernel, $K(x) = (2\pi)^{-d/2}\exp\left(-1/2x^T x\right)$, is used.

- Rényi entropy: quantifies the uncertainty in wind forecast errors

$$H_\alpha(X) = \frac{1}{1-\alpha}\log_2 \sum_{i=1}^{n} p_i^\alpha$$

  - Large values of α favor high probability events, whereas small values of α weight all of the instances more evenly.

- Heat maps: allow the operator to simultaneously see the timing and magnitude of forecast errors

Data Summary

- Wind power forecast errors:

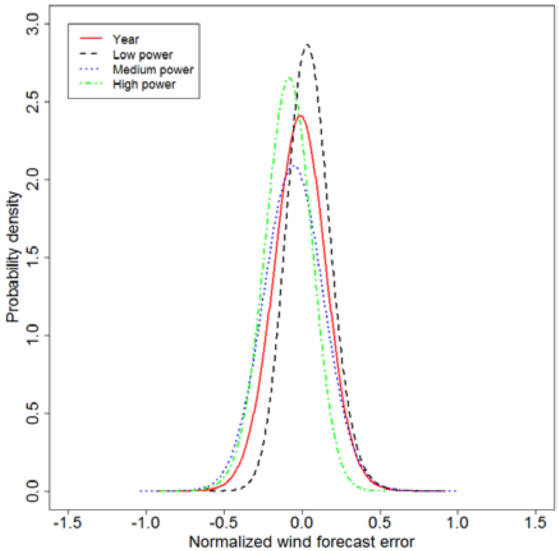
$$e_w = P_{wf} - P_{wa}$$

- The 1-hour-ahead forecasts for the six countries were synthesized using a 1-hour-ahead persistence approach.
- The day-ahead forecasts were estimated using different methodologies for the six countries.

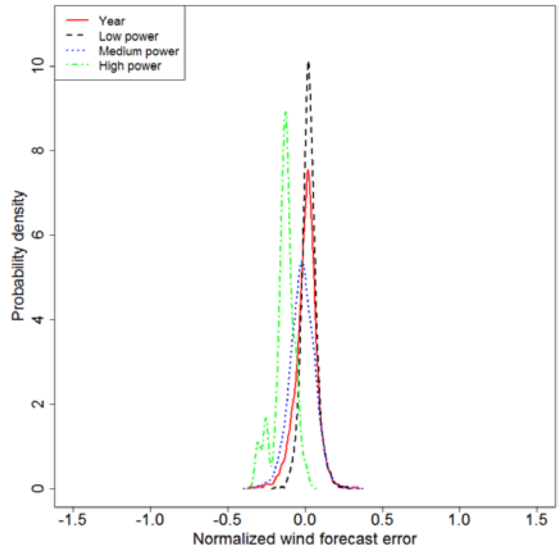
Country	Year	Capacity (MW)	Wind Power Plants
United States (ERCOT)	2010	9,000	Concentrated
Finland	2012	130	23 wind plants
Spain	2011	14,000	Well dispersed
Denmark	2012	3,265	Well dispersed
Norway	2011	284	4 wind plants
Germany	2010	26,000	Well dispersed

Distributions at Different Wind Power Levels

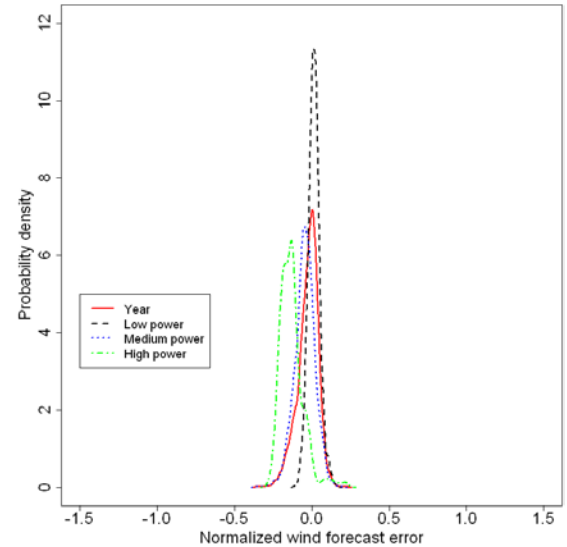
United States



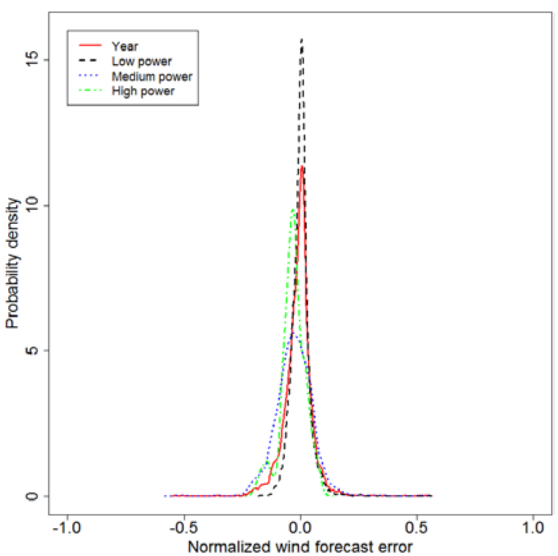
Finland



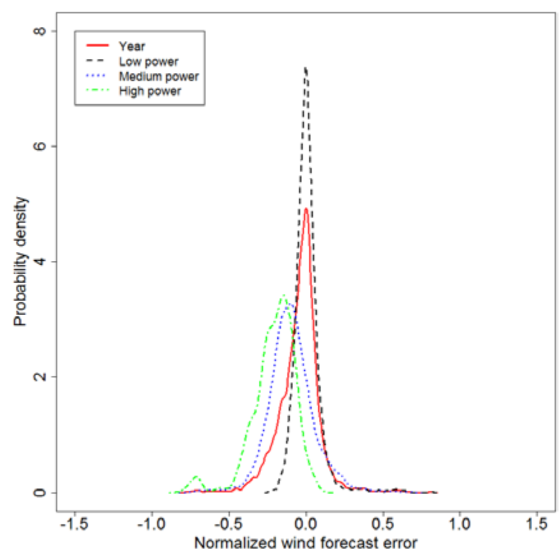
Spain



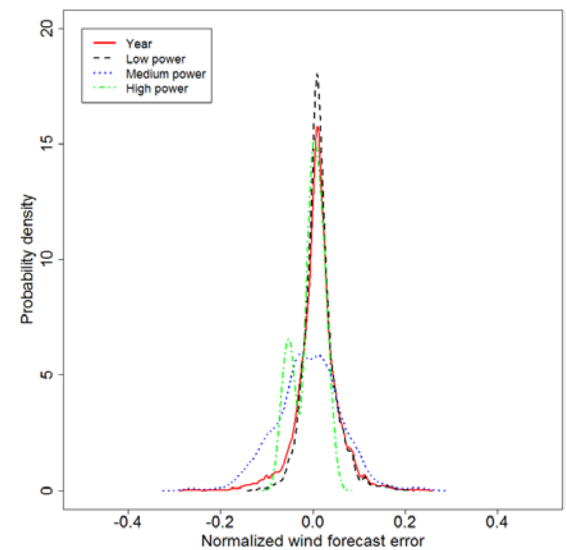
Denmark



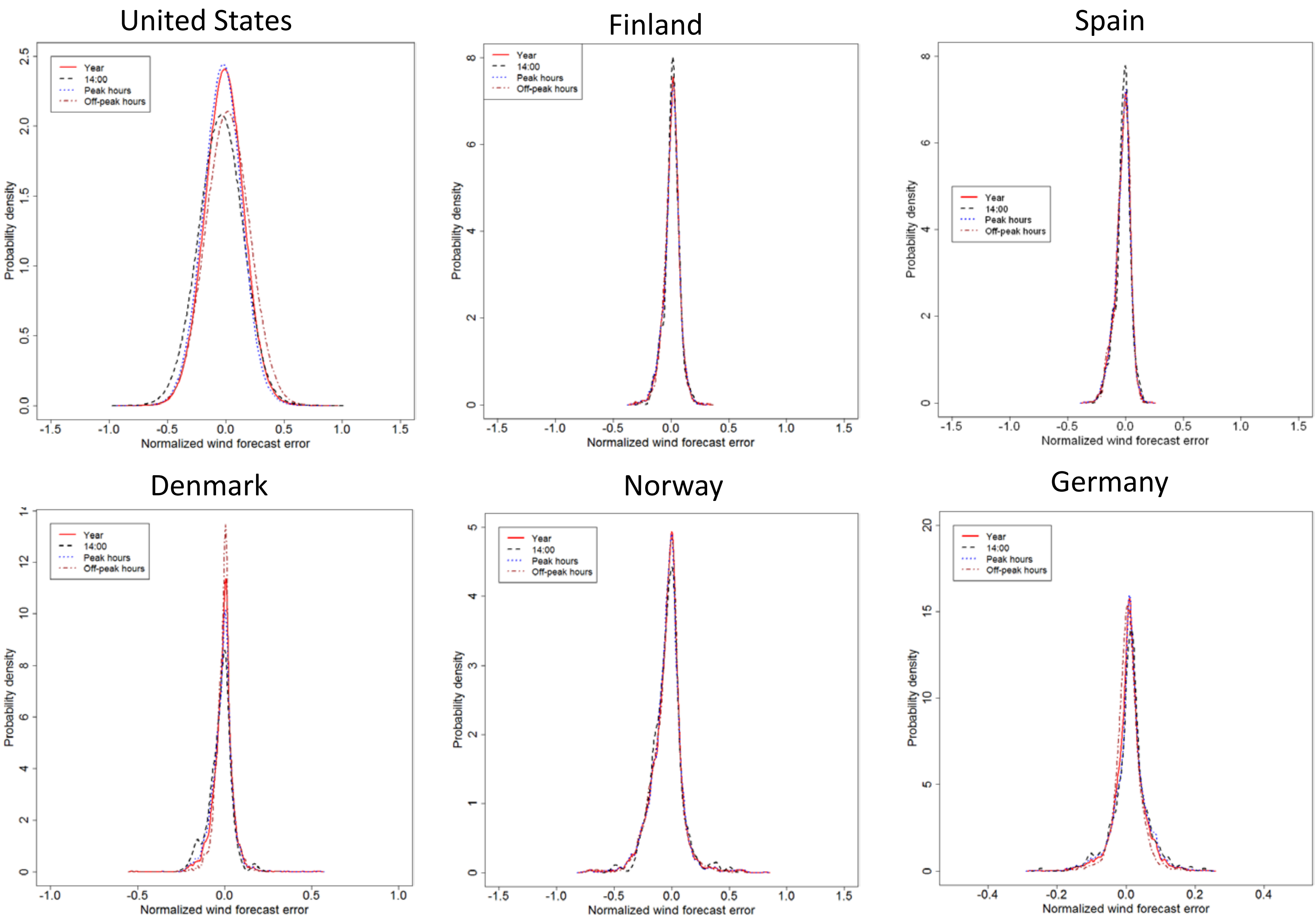
Norway



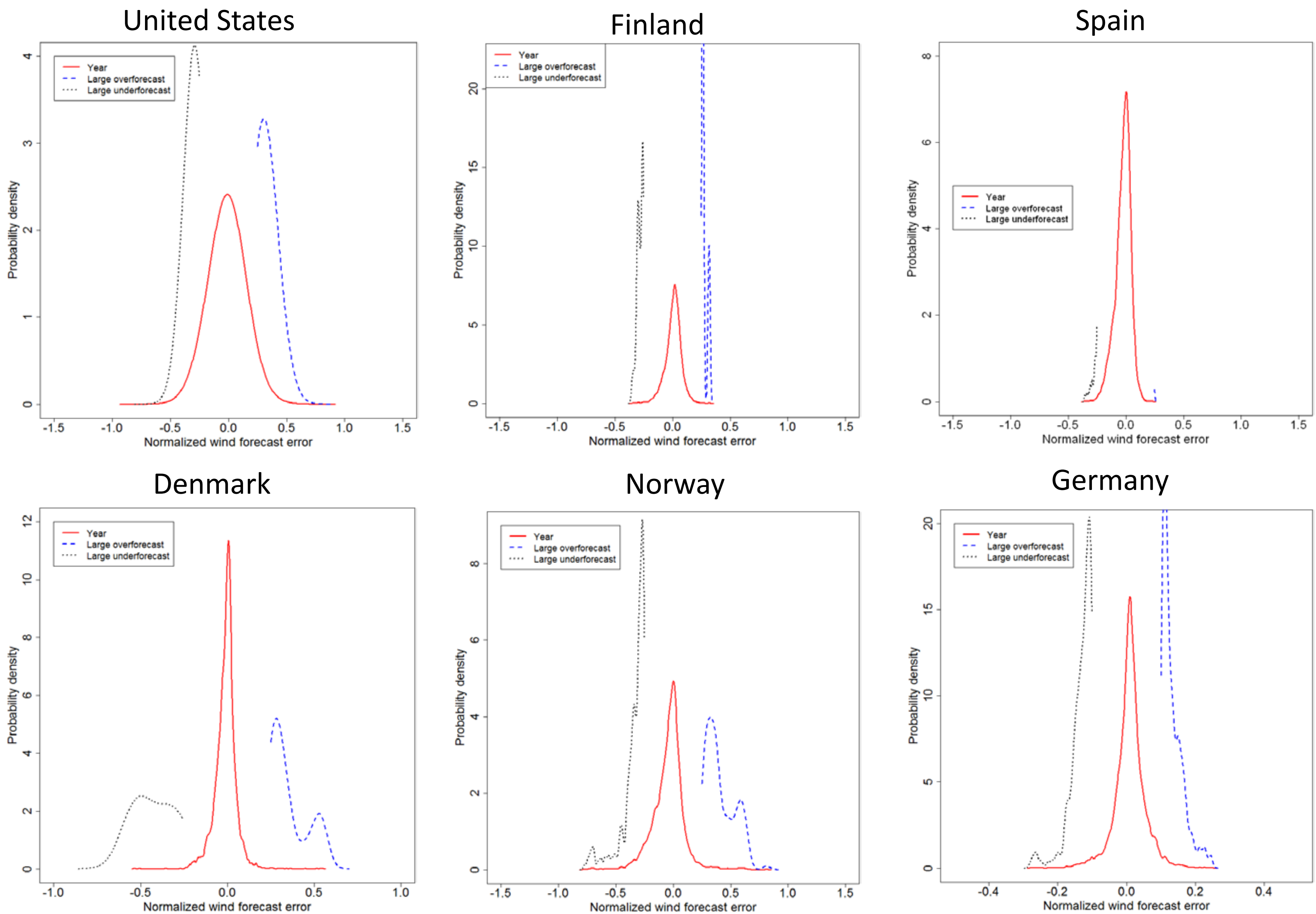
Germany



Distributions at Different Hours

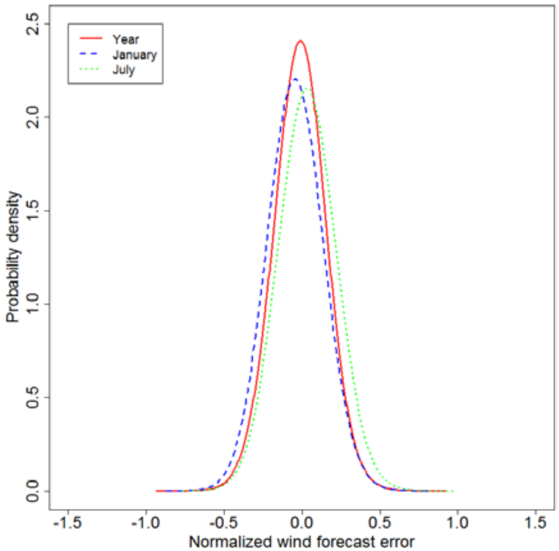


Distributions of Extreme Wind Forecast Errors

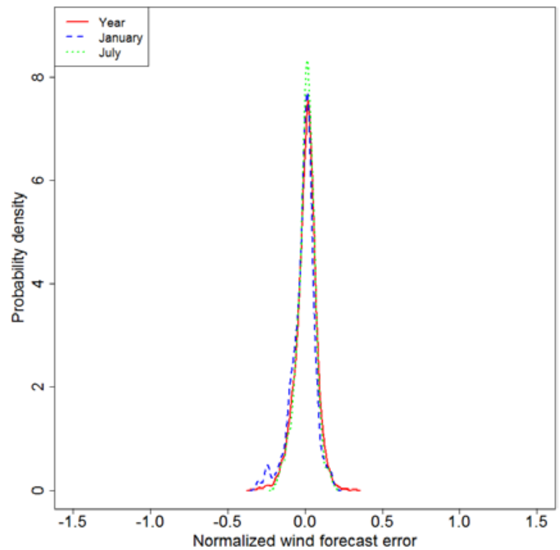


Distributions During Different Seasons (Summer and Winter)

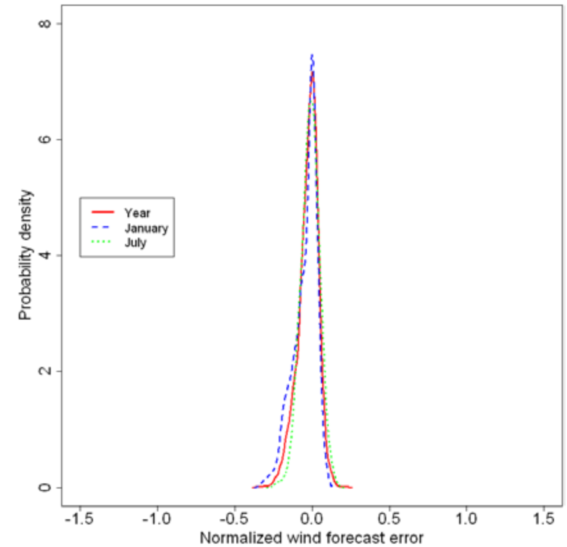
United States



Finland



Spain



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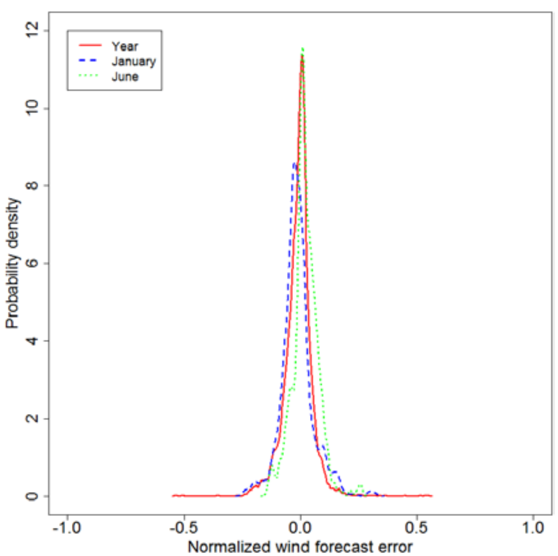

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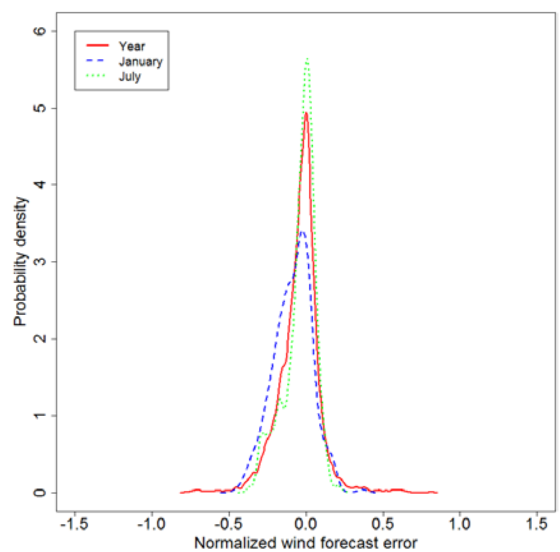
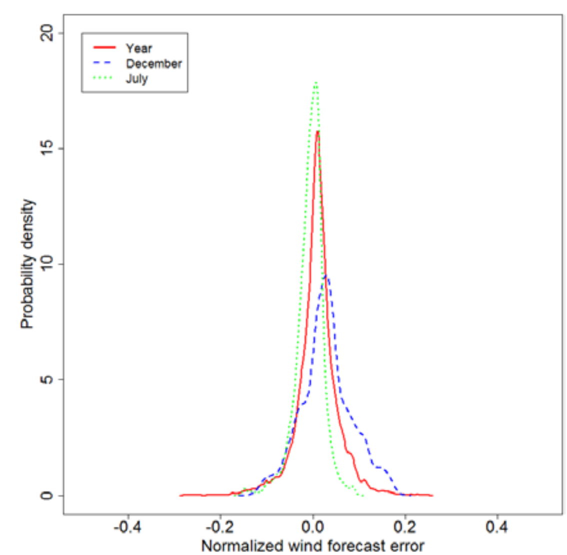
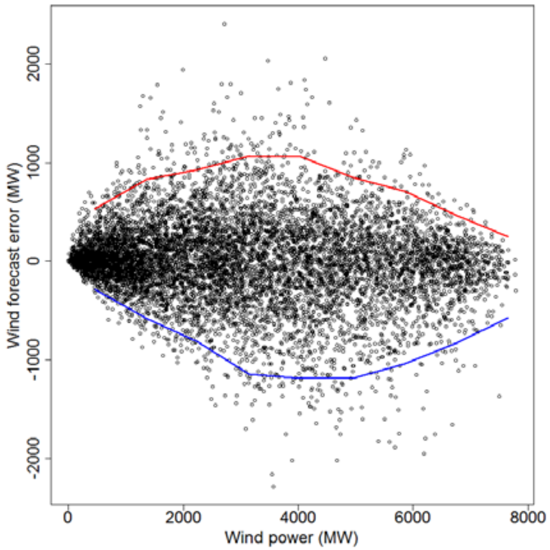


Germany

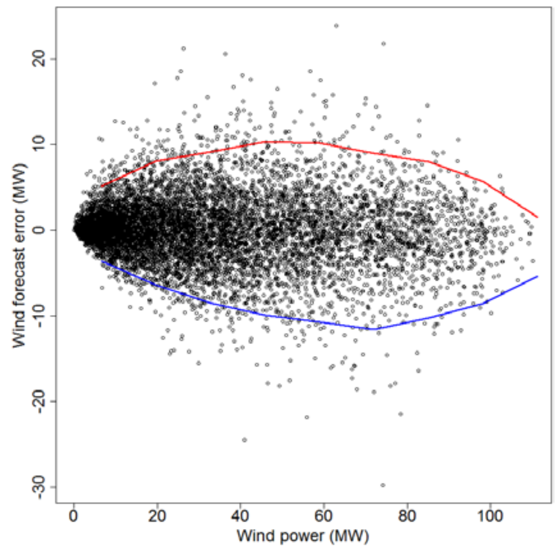


95th Percentiles of 1-Hour-Ahead Forecast Errors

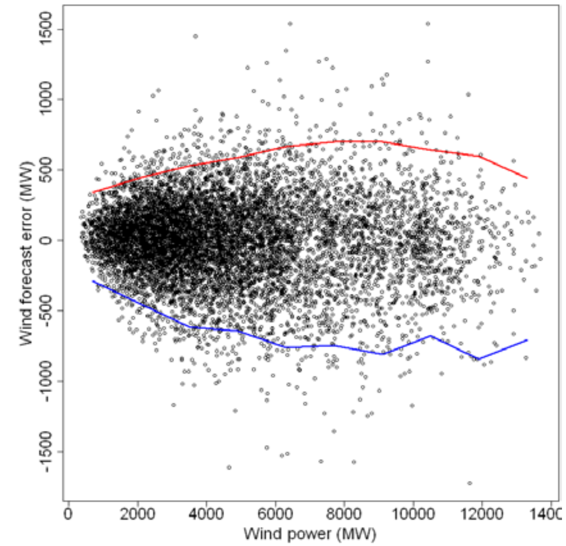
United States



Finland



Spain



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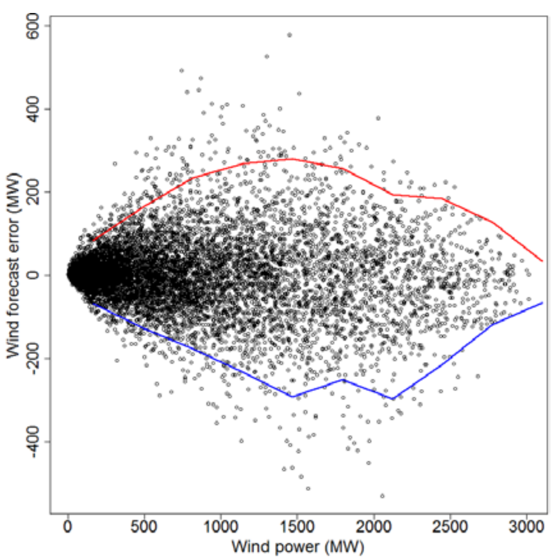

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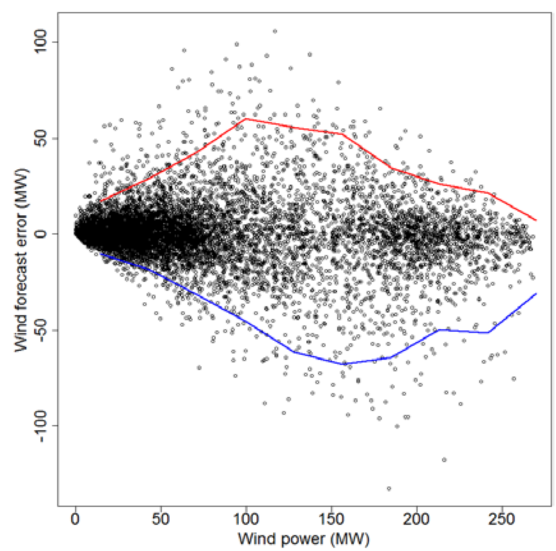
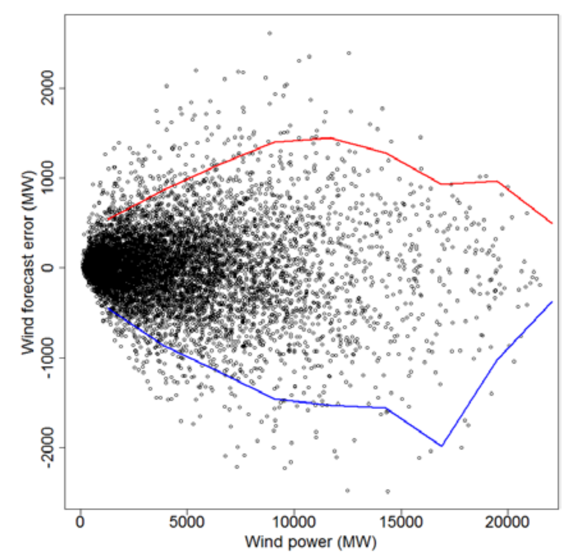
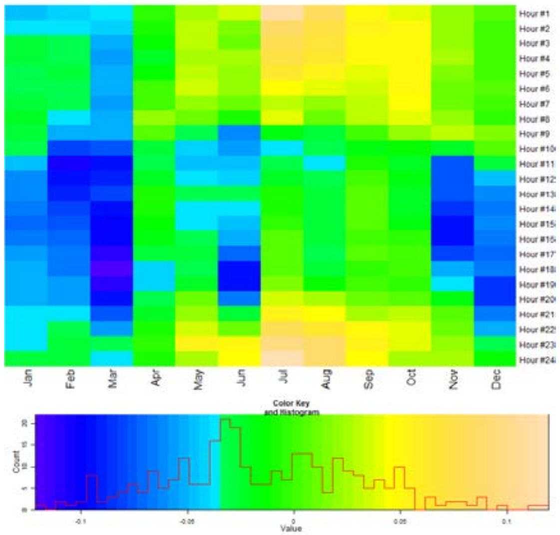


Germany



Heat Map of Day-Ahead Forecast Errors

United States



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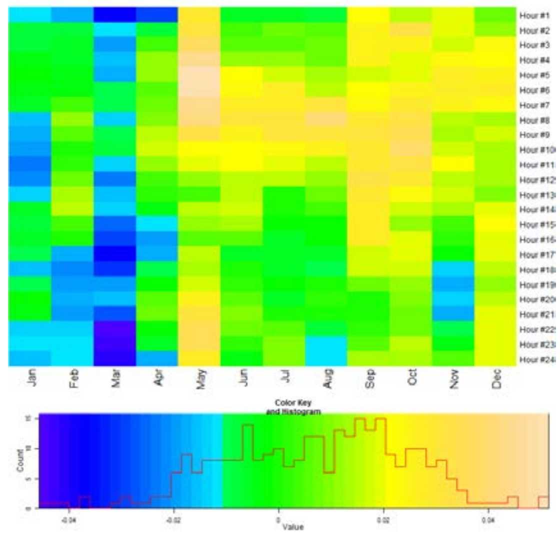

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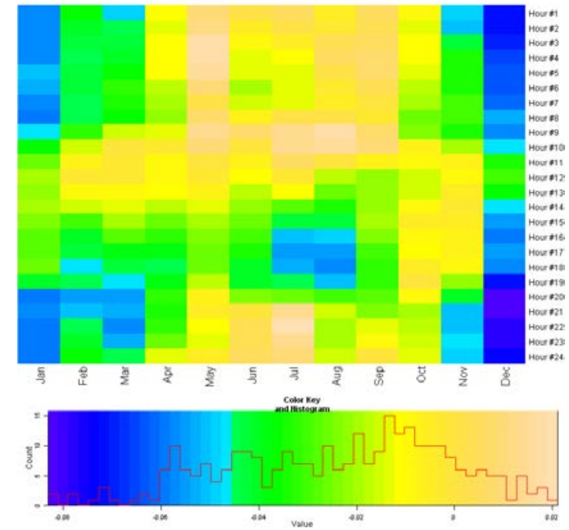

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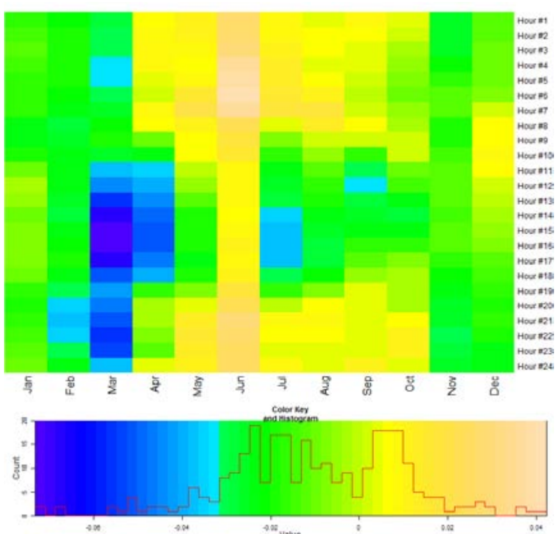

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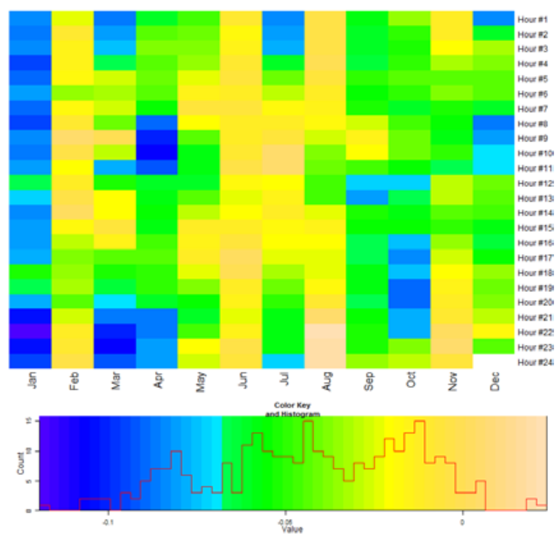

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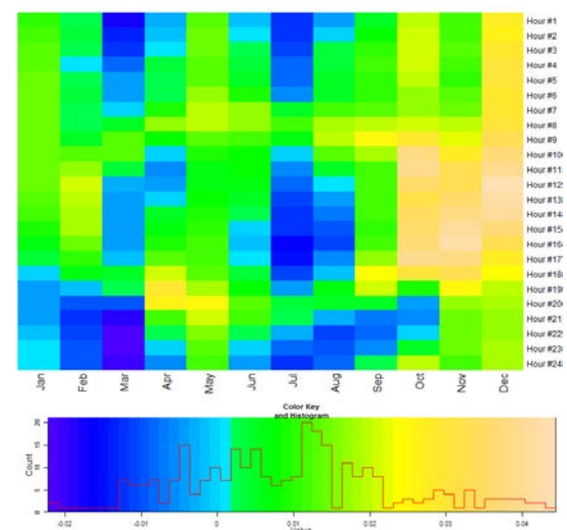
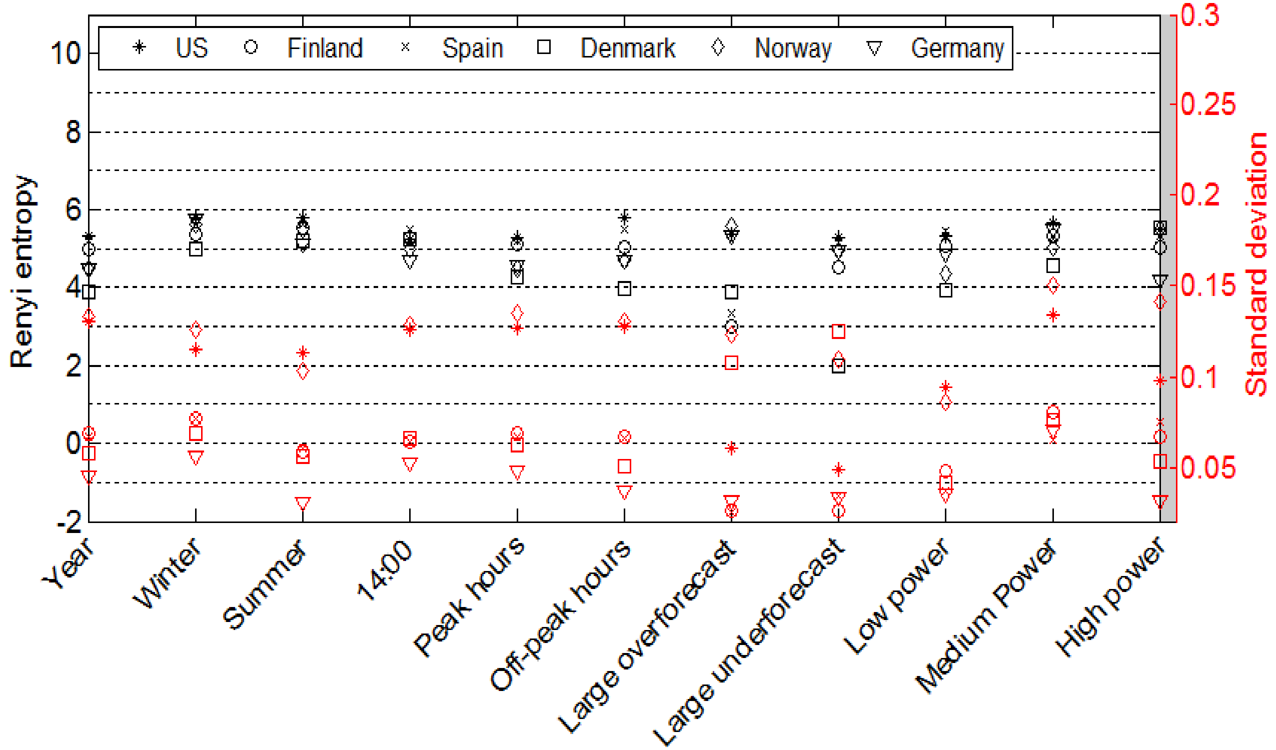


Comparison of Uncertainty in Wind Forecasting

- According to the *Rényi entropy* metric, wind forecasting in the Danish power system maintains a relatively lower level of uncertainty for most scenarios.
- According to the *standard deviation*, there is the least uncertainty in the forecasting for the German power system, followed by the Danish power system.
- Power systems (Denmark, Germany, and Spain) with low forecast error variability have a significant amount of well-dispersed wind power.
- For most power systems, forecasts in winter generally had more uncertainty than forecasts in summer.



Concluding Remarks

- This paper compared the variability and uncertainty in wind power forecasts for multiple power systems from six countries.
  - Multimodal characteristics were observed in the extreme overforecast scenarios in the Danish and Norwegian systems, and in the high-power scenario in the German system.
  - The distribution of forecast errors in the German power system was relatively narrower than that in other countries.
  - For most power systems, more underforecast events were observed in the high-power scenario than in the low- and medium-power scenarios.
- Maximum "up" and "down" reserves were required when actual wind power generation was at medium to high percentages of the total wind capacity.
- There was generally less uncertainty in forecasting when wind power plants were dispersed throughout a wide geographic area.

Future Work

Future Work

- Investigate multiple years of wind forecasting data to obtain a general trend of forecast errors.
- Compare the different methodologies in the forecasting systems in different countries and seek to identify the possible sources of bias and errors in the forecasts.

Acknowledgement

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Questions?