Benefits of spatio-temporal modelling for short term wind power forecasting at both individual and aggregated levels

The share of wind energy in total installed power capacity has grown rapidly in recent years. Producing accurate and reliable forecasts of wind power production, together with a quantification of the uncertainty, is essential to optimally integrate wind energy into power systems. We build spatio-temporal models for wind power generation and obtain full probabilistic forecasts from 15 minutes to 5 hours ahead. Detailed analysis of the forecast performances on the individual wind farms and aggregated wind power are provided. The predictions from our models are evaluated on a data set from wind farms in western Denmark using a sliding window approach, for which estimation is performed using only the last available measurements. The case study shows that it is important to have a spatio-temporal model instead of a temporal one to achieve calibrated aggregated forecasts. Furthermore, spatio-temporal models have the advantage of being able to produce spatially out-of-sample forecasts. We use a Bayesian hierarchical framework to obtain fast and accurate forecasts of wind power generation at wind farms where recent data are available, but also at a larger portfolio including wind farms without recent observations of power production. The results and the methodologies are relevant for wind power forecasts across the globe as well as for spatial-temporal modelling in general.
Understanding energy consumption patterns of different types of consumers is essential in any planning of energy distribution. However, obtaining individual-level consumption information is often either not possible or too expensive. Therefore, we consider data from aggregations of energy use, that is, from sums of individuals’ energy use, where each individual falls into one of C consumer classes. Unfortunately, the exact number of individuals of each class may be unknown due to inaccuracies in consumer registration or irregularities in consumption patterns. We develop a methodology to estimate both the expected energy use of each class as a function of time and the true number of consumers in each class. To accomplish this, we use B-splines to model both the expected consumption and the individual-level random effects. We treat the reported numbers of consumers in each category as random variables with distribution depending on the true number of consumers in each class and on the probabilities of a consumer in one class reporting as another class. We obtain maximum likelihood estimates of all parameters via a maximization algorithm. We introduce a special numerical trick for calculating the maximum likelihood estimates of the true number of consumers in each class. We apply our method to a data set and study our method via simulation.

**Analysis of aggregated functional data from mixed populations with application to energy consumption: Aggregated Functional Data**

Understanding energy consumption patterns of different types of consumers is essential in any planning of energy distribution. However, obtaining individual-level consumption information is often either not possible or too expensive. Therefore, we consider data from aggregations of energy use, that is, from sums of individuals’ energy use, where each individual falls into one of C consumer classes. Unfortunately, the exact number of individuals of each class may be unknown due to inaccuracies in consumer registration or irregularities in consumption patterns. We develop a methodology to estimate both the expected energy use of each class as a function of time and the true number of consumers in each class. To accomplish this, we use B-splines to model both the expected consumption and the individual-level random effects. We treat the reported numbers of consumers in each category as random variables with distribution depending on the true number of consumers in each class and on the probabilities of a consumer in one class reporting as another class. We obtain maximum likelihood estimates of all parameters via a maximization algorithm. We introduce a special numerical trick for calculating the maximum likelihood estimates of the true number of consumers in each class. We apply our method to a data set and study our method via simulation.
Spatial models for probabilistic prediction of wind power with application to annual-average and high temporal resolution data

Producing accurate spatial predictions for wind power generation together with a quantification of uncertainties is required to plan and design optimal networks of wind farms. Toward this aim, we propose spatial models for predicting wind power generation at two different time scales: for annual average wind power generation, and for a high temporal resolution (typically wind power averages over 15-min time steps). In both cases, we use a spatial hierarchical statistical model in which spatial correlation is captured by a latent Gaussian field. We explore how such models can be handled with stochastic partial differential approximations of Matérn Gaussian fields together with Integrated Nested Laplace Approximations. We demonstrate the proposed methods on wind farm data from Western Denmark, and compare the results to those obtained with standard geostatistical methods. The results show that our method makes it possible to obtain fast and accurate predictions from posterior marginals for wind power generation. The proposed method is applicable in scientific areas as diverse as climatology, environmental sciences, earth sciences and epidemiology.

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Statistical modelling of space-time processes with application to wind power.

Short-term wind power forecasts together with a quantification of uncertainties are required for the reliable operation of power systems with significant wind power penetration. A challenge for utilizing wind power as a source of energy is the intermittent and hardly predictable nature of wind. This thesis aims at contributing to the wind power literature by building and evaluating new statistical techniques for producing forecasts at multiple locations and lead times using spatio-temporal information. By exploring the features of a rich portfolio of wind farms in western Denmark, we investigate different types of models and provide several forms of predictions. Starting with spatial prediction, we then extend the methodology to spatio-temporal prediction of individual wind farms and aggregated wind power at monitored locations as well as at locations where recent observations are not available. We propose spatial models for predicting wind power generation at two different time scales: for annual average wind power generation and for a high temporal resolution (typically wind power averages over 15-min time steps). In both cases, we use a spatial hierarchical statistical model in which spatial correlation is captured by a latent Gaussian field. We explore how such models can be handled with stochastic partial differential approximations of Matérn Gaussian fields together with integrated nested Laplace approximations. We show that complex hierarchical spatial models are well suited for wind power data and provide results in reasonable computational time. Moreover, the hierarchical approach for obtaining predictions at a high temporal resolution is found to produce accurate predictions with improved performance compared to a standard geostatistical method at a small additional computational cost. The use of the integrated nested Laplace approximations is motivated by the desire to produce forecasts on large data sets with hundreds of locations, which is critical during periods of high wind penetration. Subsequently, the extension from spatial to spatio-temporal models is given. Three different hierarchical models are developed for obtaining probabilistic wind power forecasts. First, a time series model consisting of an autoregressive process with a location specific intercept is considered. This approach gives satisfactory results for individual forecasts but fails to generate calibrated aggregated forecasts. The second approach has a common intercept for all farms and a spatio-temporal model that varies in time with first order autoregressive dynamics and has spatially correlated innovations given by a zero mean Gaussian process. The third model, which also has a common intercept as well as an autoregressive process to capture the local variability and the spatio-temporal term from the second approach, is able to produce reliable individual and aggregated forecasts for multiple lead times. Finally, very-short-term wind power forecasting is considered. Probabilistic forecasts from 15 minutes up to two hours ahead are produced by using anisotropic spatio-temporal correlation models to account for the propagation of weather fronts and a transformed latent Gaussian field is used to accommodate the probability masses that occur in wind power distribution due to chains of zero measurements. Using what is called kriging equations, even the simplest proposed covariance model is able to produce calibrated spatio-temporal predictions of wind power production.
A Spatial Model for the Instantaneous Estimation of Wind Power at a Large Number of Unobserved Sites

We propose a hierarchical Bayesian spatial model to obtain predictive densities of wind power at a set of un-monitored locations. The model consists of a mixture of Gamma density for the non-zero values and degenerated distributions at zero. The spatial dependence is described through a common Gaussian random field with a Matérn covariance. For inference and prediction, we use the GMRF-SPDE approximation implemented in the R-INLA package. We showcase the method outlined here on data for 336 wind farms located in Denmark. We test the predictions derived from our method with model-diagnostic tools and show that it is calibrated.

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