UiO:Energy. Thematic Research Groups (TRG), application

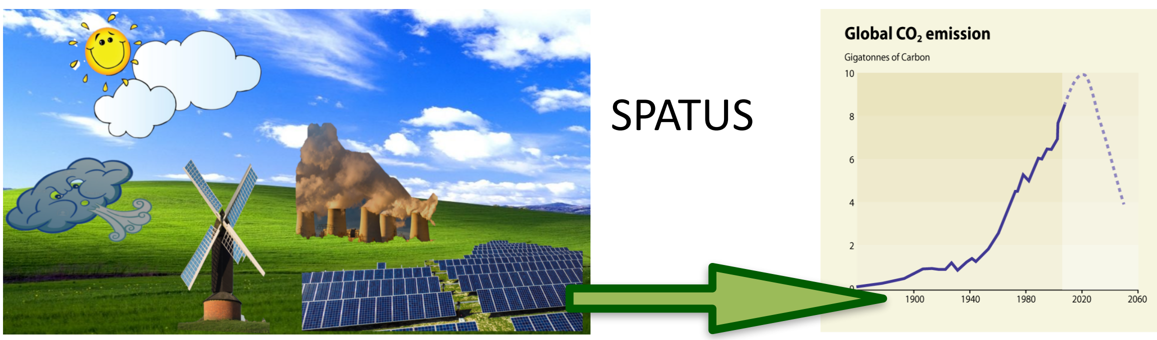
Spatial-Temporal Uncertainty in Energy Systems (SPATUS)

TRG leader: Professor Fred Espen Benth
E-mail address: fredb@math.uio.no

Abstract

The reduction of carbon emission along with meeting increased demand for electricity is a major challenge in most power systems worldwide. The future carbon emission targets can only be met by an increased share of renewable power generation together with nuclear. Power generated by wind and photovoltaic (PV) are intermittent, and depend both on underlying weather factors like cloud cover and wind, as well as temperature which also is a fundamental driver of demand. In this TRG we propose to develop new and sophisticated dynamical models for temperature, wind and cloud cover which explains the uncertainty in their time and space evolution (so-called "spatial-temporal random fields"), in particular, the space-time dependencies and marginal distribution. The spatial-temporal random fields will combine physical dynamics with a quantification of the uncertainty inherent in weather dynamics. Furthermore, the TRG will have a particular view towards the stochastic modelling of clouds, a field vastly open for new and exciting mathematical modeling and analysis with impact on the forecasting and prediction of PV production. The new random models will be suitable for several applications to energy systems. We aim at studying the uncertain production from wind and PV installations based on the wind, temperature and cloud cover pattern. Further, in a geographically wider model we analyse the optimal spatial allocation of PV installations and wind parks under constraints on capacity and societal/political feasibility. The goal of the optimisation is to ensure the best possible stability in the production patterns from the locally intermittent energy generators. Such a study will heavily depend on the spatial correlation structure of the weather fields. Finally, we aim at upscaling our spatial-temporal models for the weather variables to analyse the optimal development of the energy system as a whole under given targets for emissions. Optimality will take into account economic and environmental restrictions as well as prospected demand pattern.

The TRG will be a collaboration between the Departments of Mathematics and Technology Systems, UiO. It will also involve a collaboration with experts in high-dimensional stochastics and energy systems from Universities of Vienna and Reading. A PhD and post doc will be trained in the TRG.



Description of TRG and TRG project

The proposed SPATUS TRG will contribute with new and novel research within "Energy Systems" and "Energy Transition and Sustainable Societies", two of the four main research areas in the focus of UiO:Energy.

Description of the research project of the SPATUS TRG

The SPATUS project has two overall main research goals:

1) **Develop novel spatial-temporal random fields describing the joint dynamics of the weather variables clouds, wind and temperature**, and

2) **Develop realistic plans for optimal integration of renewable power generation into an energy system in transition towards sustainable production reaching overall emission goals**.

To reach these two goals, new theory and analysis in both mathematics and system theory must be developed. Existing reduced-form stochastic models accounting for the space-time dependencies across weather variables like wind and temperature call for development, and dynamics for cloud cover is very little understood. The outcome of the project will be new insights to the interaction between renewable power generation, the space-time random dynamics of weather variables and the prospects how to reach emission goals with respect to future demand patterns. SPATUS will generate research and knowledge that will be of value for policy makers and energy system operators, as well as generators of renewable (and non-renewable) power.

The energy systems today consist typically of a mixture of renewable, fossil-fuelled and nuclear power. How the energy mix is, depends on the geographical area in question. In the developed world, the generation of energy is not sustainable regarding meeting the emission targets set in global agreements. The simple question is: how should fossil-fuelled generators be phased out and sustainable production be integrated to meet emission targets, societal constraints and future energy demand? The answer to this is highly non-trivial, but requires a careful analysis of how the renewable generation from wind and PV plants interact with demand, largely driven by temperature, dynamically over time and geographical area. This interaction is very complex, due to dependencies between weather variables along with challenging constraints given by society. The latter include problems related to the areas required for wind mill farms and/or PV installations which is not necessarily compatible with the public or policy views. On top we need to account for climate change in a long-term perspective.

There exist meteorological dynamical models for weather systems on one hand, and random fields in time and space describing probabilistic features on the other hand. In a specified geographical area (for example, the UK or Germany, where we are interested in studying the energy system), we aim at an "operational" space-time stochastic model accounting for physical facts as well as statistically observable characteristics. With "operational", we mean mathematical models which can be estimated to data and being feasible for further analysis like simulation of the energy systems with wind and PV generation, say.

Stochastic partial differential equations (see Peszat and Zabczyk [PZ]) constitute a versatile class of models which has the potential of combining physics with randomness. For example, temperature may generically be modelled (in time t and space x) as

$$dT(t,x) = \mathscr{L}T(t,x)dt + \sigma(t)dW(t)(x)$$

Here, W is noise in time and space (e.g., white noise) and $\sigma(t)$ is a volatility operator. The parabolic operator $\mathscr{L}$ is a second-order partial differential operator, and may be given by physical and meteorological knowledge. But often local variations due to topography may create huge challenges in the exact description of it. Also, the model is not perfect, so one can collect much of non-explained variability in noise terms. By modern techniques from neural networks and machine learning, an idea not explored in the literature is to learn the parabolic operator from data, as well as the correlation structure of the time-space noise.

We aim for a joint model, which means that we want to have a three-variate stochastic model for the spatial-temporal dynamics of temperature, wind speed and cloud cover. Cloud cover and wind speed are of course main ingredients of PV and wind mill power generation, while temperature is a known driver of demand. Some initial attempts of marginal modelling of space-time behaviour of wind and temperature fields purely based on statistical descriptions can be found in Benth and Saltyte Benth [BSB].

With the model, we want to connect spatial and temporal dependencies, both using causal and stochastic modelling. Here the nature of the deterministic parts can be modelled using physical knowledge, but also by appealing to machine learning techniques. There exist some theory on modelling multivariate spatial-temporal noise processes (see [BK]), but the knowledge for such trivariate random fields is highly limited in the current context.

A challenging variable to model is cloud cover. Clouds are three dimensional objects which may or may not have well-defined borders. One has measurements from satellites and ground cameras, and the radiation through the cloud determines to a large degree the PV production at given locations. Clouds move obviously with the wind, but wind patterns are different in the atmosphere than at ground-level, which is the relevant altitude for wind mills. On the other hand, wind speeds at ground level also influences PV generation, as there is a cooling effect increasing the efficiency of panels. So, we may consider splitting the wind speed component into a bivariate model, one for atmospheric hight and another at earth's surface. Also, the direction of the wind matters, so we could further refine into a three dimensional wind field, significantly complicating the modelling.

Coming back to stochastic modelling of clouds, one could do a model which looks at the "density" of clouds in time and space, that is, giving a number between 0 and 1 for how well solar irradiation travels trough the cloud. Here 1 can refer to blue sky, while 0 for no irradiation. Each point in time and space will have a number between these two levels. This will provide a random field model which potentially could mimic the situation rather well, being appropriate for joint modelling. However, to model random fields which are bounded between levels are not simple, although we have some clear ideas on how to do this in the this context based exponential transform of ambit fields (see [BNBV]) driven by positive Levy noise.

There is a zoology of different clouds with different absorption and reflection properties (see Lohmann et al. [LLM]). A complete new and novel approach would be to look for models of clouds based on so-called random sets, that is, geometric objects moving randomly in space with time. Associated to these random sets, which describe the shape of clouds, one could have features like droplet shape and concentration to form a total description of the cloud characteristics. One could also look at the same modelling collapsed into the plane, mimicking the clouds seen from above (by satellites). There exist a general theory on random sets (see Molchanov [M]), but very limited knowledge exists for the time dynamics of such sets (even Brownian motion is not well-studied), and even less for combining such models with other features and variables. Open questions include estimation and simulation of random set cloud models.

To estimate multivariate random field models to data, new techniques must be developed. For wind and temperature fields, approaches from functional data analysis (see Bosq [B] for a theoretical introduction) may be appropriate to use, however, one must introduce new theory for covariance operators in product Hilbert spaces (to capture covariances in particular). A combination of ground-station local measurements and satellite data should be combined and a new way with statistical theory. Estimating cloud cover models may be significantly more challenging, especially models based on random sets. Here the literature is very thin, but using the so-called selection function one has (theoretically) the probability distributions of random sets which therefore can make the basis for statistics. Cloud cover data are typically images from satellites or ground cameras, which must be integrated into statistics for the models. New results here will be exciting developments of the mathematics and application of random set models.

With models for weather variables available, the next step is to apply them to energy systems analysis. The main target for the "Energiewende" that takes place in most energy markets worldwide is the transition from "fossil-fuelled" to "green" societies meeting the carbon emission targets set by international agreements. Energy systems must be designed to meet the future demand, as well as economic, technological, geographical and policy constraints. To plan realistically for such transition is a non-trivial problem, which has been addressed in papers by Zeyringer et al. [Z]. Obviously, the power generation from

PV and wind farms depend on the weather conditions in the geographic region in question, and a stochastic model for this is a crucial input in understanding the impact of new renewable sources substituting coal or gas plants, say. Renewables are highly intermittent, unlike gas and coal fired power generation, and introduce weather uncertainty in a much more complex fashion than simply temperature on the demand side. The temporal variability is important in timing of production, and the spatial variability in the geographical diversification on plants. The output from SPATUS could solve the existing challenge on how to represent the variability of the weather and demand and thus design weather and climate resilient renewable based energy systems:

In SPATUS, we focus first on a (possibly small-scale) geographical problem in finding optimal locations for power plants, being wind farms of PV installations. The problem can be phrased as follows. Given a budget constraint, either as output capacity or financial (or both), find the optimal distribution of power plants in a given region. Optimality is measured as a geometry of plants offering the smoothest production profile of power. In a recent study (Sauri et al. [SC]), the authors considered this question for PV installations in a region of South Africa, and found that diversifying into several smaller plants yielded a much more stable power generation than one single plant. This is similar to financial portfolio theory, where the general advice is “not to put all eggs into one basket”. As the optimal diversification depends on the spatial cloud cover dynamics (for PV) and spatial wind patterns (for wind mills), this is a highly non-trivial stochastic control problem. Production depends on technologies (but idealised, via for example Betz’ law in case of wind power production), and we may also include geographical limitations on which areas to use for these installations. There are also problems for wind farms being “too close”, as they influence the wind fields in the wake of the plants. Using our proposed models, we have available a precise description of the spatial dependencies in the weather variables being a basis for setting up such a control problem.

Another exciting application of our spatial-temporal weather models is to analyse the transition of the energy system from carbon-intensive to renewable. If one looks at the UK energy system, say, such a transition must include a mix of different power generation sources. Where to build new wind and solar parks depend on spatial variability of the weather factors (see above discussion), but also on demand patterns in conjunction with transmission lines as well as area constraints. The novelty in SPATUS is that such temporal problems can be studied based on the proposed models which take into account the fine-scale properties of random fields. To have a feasible study of the energy system, these models must be upscaled to a coarser grid, but this upscaling will transfer the fine scale properties in a statistically sound way. Dependencies (i.e., spatial and temporal correlation) on fine and large scales will be logically connected. Moreover, different data sources can be incorporated to modify, correct and/or calibrate the models at different grid levels.

In existing studies, scenarios generated from meteorological models have been applied in the analysis of the transition of energy systems reaching emission targets. With the approach proposed in SPATUS, the scenarios can be generated from random fields where one has full control over the probabilistic properties, which means that the distributions of the outcomes from such an analysis (e.g. installed capacities of different power sources, probability of reaching targets, etc…) become sound. Sensitivity analysis can also be performed, crucial in understanding how the reached solutions for the energy systems are stable (or unstable) with respect to weather change, say. For example, in the future we may get more extreme wind patterns. Too much wind may require more robust (and more expensive) wind mill technology, or, that one is in situations where the mills must be stopped to prevent damage. Another aspect is cloud formation, which is also uncertain in future weather systems. A natural question to ask is therefore how robust is the solar panel installation plans derived from the analysis towards cloud formation. Important to highlight is that our models are based on multivariate random fields, which will not only account for the marginal probability distributions, but also include the co-variability between factors in the system. It is a challenging optimisation problem to account for these factors together with constraints in the system, being geographical, physical or politicial.

The SPATUS research project is divided into four work packages:

Work package 1
Develop trivariate (or higher-dimensional) stochastic partial differential equations taking physical and probabilistic properties of weather factors (cloud, wind, temperature) into account. A special emphasis on

development of estimation and simulation tools, implemented in suitable software and analysed form a mathematical point of view. Estimation of covariance operators and other parameters using functional data analysis. Machine learning to reveal parameters from data to model. Simulation methods based on Monte Carlo and techniques from partial differential equations.

Work package 2
Develop temporal random set models for clouds, including stochastic differential equations and noise processes like Brownian motion in random sets. Inclusion of features like irradiation and droplet size, and multivariate models where wind field at atmospheric level is included. Development on new theory for simulation and estimation, latter based on functional data analysis and selection function theory. Integration of data from ground-cameras and satellite images. Connection to ground level wind fields and temperature.

Work package 3
Study optimal allocation of farms given space-time weather models. Diversification with aim of maximal temporal stability of production. Given constraints are geographical and capacities, and budgets for total production costs. Production from PV and wind mills based on models for typical farms and technologies, but where also different technologies can be accounted for. Optimization based on stochastic dynamic control and deep learning methods, as well as Monte Carlo based simulation blended with methods from partial differential equations.

Work package 4
Upscaling of proposed models to a suitable coarse grid in time and space via integration. Development of efficient sampling techniques from coarse-grid model honouring probabilistic features like geographical and cross-weather dependencies. Develop case studies for given regions like UK and Germany, where plans for transition of energy system given future demand pattern and emission targets are reached. Inclusion of relevant policy and other constraints, and sensitivity analysis to reveal crucial factors impacting the plans. Analysis of the stability of the system based on sensitivity analysis.

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SPATUS organisation, PIs and members

The SPATUS TRG is a collaboration between the Departments of Mathematics and Technology Systems (ITS), at the Faculty for Mathematics and Natural Sciences at UiO. The TRG is led by professor Fred Espen Benth (Math), who is also a principal investigator in the TRG together with associate professor Marianne Zeyringer (ITS). The two-year program will involve active collaboration with associate professor Christa Cuchiero from Vienna University of Economics and Business**,** and associate professor David Brayshaw from Reading.