Chance-constrained optimal power flow with non-parametric probability distributions of dynamic line ratings

Compared to Seasonal Line Rating (SLR), Dynamic Line Rating (DLR) allows for higher power flows on overhead transmission lines, depending on the actual weather conditions. Nevertheless, the potential of DLR has to be traded off against the additional uncertainty associated with varying ratings. This paper proposes a DC-Optimal Power Flow (DCOPF) algorithm that accounts for DLR uncertainty by means of Chance-Constraints (CC). The goal is to determine the optimal day-ahead dispatch taking the cost of reserve procurement into account. The key contribution of this paper consists in considering both non-parametric predictive distributions of DLR and the combined wind power uncertainty in the optimization problem. Our results highlight the benefits of DLR in wind-dominated power systems, assuming typical risk aversion levels in the line rating estimation.
Optimal allocation of HVDC interconnections for exchange of energy and reserve capacity services

The increasing shares of stochastic renewables bring higher uncertainty in power system operation and underline the need for optimal utilization of flexibility. However, the European market structure that separates energy and reserve capacity trading is prone to inefficient utilization of flexible assets, such as the HVDC interconnections, since their capacity has to be ex-ante allocated between these services. Stochastic programming models that co-optimize day-ahead energy schedules with reserve procurement and dispatch, provide endogenously the optimal transmission allocation in terms of minimum expected system cost. However, this perfect temporal coordination of trading floors cannot be attained in practice under the existing market design. To this end, we propose a decision-support tool that enables an implicit temporal coupling of the different trading floors using as control parameters the inter-regional transmission capacity allocation between energy and reserves and the area reserve requirements. The proposed method is formulated as a stochastic bilevel program and cast as mixed-integer linear programming problem, which can be efficiently solved using a Benders decomposition approach that improves computational tractability. This model bears the anticipativity features of a transmission allocation model based on a pure stochastic programming formulation, while being compatible with the current market structure. Our analysis shows that the proposed mechanism reduces the expected system cost and thus can facilitate the large-scale integration of intermittent renewables.

Peer-to-peer and community-based markets: A comprehensive review

The advent of more proactive consumers, the so-called “prosumers” with production and storage capabilities, is empowering the consumers and bringing new opportunities and challenges to the operation of power systems in a market environment. Recently, a novel proposal for the design and operation of electricity markets has emerged: these so-called peer-to-peer (P2P) electricity markets conceptually allow the prosumers to directly share their electrical energy and investment. Such P2P markets rely on a consumer-centric and bottom-up perspective by giving the opportunity to consumers to freely choose the way they buy their electric energy. A community can also be formed by prosumers who want to collaborate, or in terms of operational energy management. This paper contributes with an overview of these new P2P markets that starts with the motivation, challenges, market designs moving to the potential future developments in this field, providing recommendations while considering a test-case.
Online adaptive clustering algorithm for load profiling

With the large-scale deployment of smart metering, energy sector is facing 'Big Data' related challenges. While metered customers generate streams of data, load profiling methods are not taking advantage of this structure. Indeed, insights on the demand are traditionally provided by static typical load profiles. Renewable energy sources generate intermittency in the production and subsequently uncertainty in aligning the generation to the demand at any time. This work proposes a new view on load profiling that takes benefit of the stream structure of the data, an adaptive and recursive clustering method that generates typical load profiles updated to newly collected data. The online adaptive clustering algorithm is based on an online K-means approach using a dynamic time warping based distance associated with a facility location to adjust the number of typical load profiles. The performance of the algorithm is evaluated on a synthetic dataset and applications are presented on real-world dataset from both electricity and central district heating.

Energy forecasting in the big data world

Modern information and communication technologies have brought big data to virtually every segment of the energy and utility industries. While forecasting is an important and necessary step in the data-driven decision-making process, the problem of generating better forecasts in the world of big data is an emerging issue and a challenge to both industry and
academia. This special section aims to collect top-quality forecasting articles that document cutting-edge research findings and best practices on a wide range of important business problems in the energy industry. Our emphasis is on big data, such as forecasting with high resolution data, the use of high-dimensional processes, forecasting in real-time, and the use of non-traditional data and variables.

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A DSO-level contract market for conditional demand response
This paper proposes a fixed-term (e.g., monthly) Demand Response (DR) contract market. Based on the outcomes of this market, the Distribution System Operator (DSO) pays DR aggregators to modify power consumption within a fixed window each day. Two contract types are introduced: Scheduled contracts require the DR daily, while conditional contracts require the DR after an activation signal from the DSO. Asymmetric block offers, introducing integer variables, are used to model DR with a rebound effect, potentially causing the DR offers to clear at a loss for the aggregators. Without an activation cost for conditional contracts, the DSO has the incentive to dispatch DR, despite consumer discomfort exceeding grid security benefits. Thus, the proposed market incorporates side-payments. A numerical study shows that among all DR services considered, the proposed market determines the optimal service for the whole system, ensuring the profitability of each market participant.

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A Mid-Term DSO Market for Capacity Limits: How to Estimate Opportunity Costs of Aggregators?
A large number of mechanisms are proposed to manage potential problems in distribution networks caused by the participation of distributed energy resources (DERs) in the wholesale markets. In this paper, we first introduce a practical and straightforward mechanism, based on capacity limits, which avoids conflicts between the transmission system operator and the distribution system operators (DSOs). Using a large number of real electric vehicle (EV) commercial charging stations we then show how an EV aggregator can forecast the opportunity cost incurred by offering a mid-term capacity limit service to the DSO. This cost is computed based on the estimated profit that the aggregator could gain in the day-ahead and real-
time markets. The proposed methodology guarantees robustness against evolving EV uncertainty, both in terms of service delivery and driving requirements. It also allows the use of a variety of timeseries forecasting methods without forecasting electricity prices and EV scenarios. The results of our empirical analysis show the exponential increase of opportunity cost and the considerable increase of the prediction intervals as the capacity limit decreases. The produced offering curves can be used as an indication of the underutilization cost of DERs caused by the DSO's limitations.

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**An Integrated Market for Electricity and Natural Gas Systems with Stochastic Power Producers**
In energy systems with high shares of weather-driven renewable power sources, gas-fired power plants can serve as a back-up technology to ensure security of supply and provide short-term flexibility. Therefore, a tighter coordination between electricity and natural gas networks is foreseen. In this work, we examine different levels of coordination in terms of system integration and time coupling of trading floors. We propose an integrated operational model for electricity and natural gas systems under uncertain power supply by applying two-stage stochastic programming. This formulation co-optimizes day-ahead and real-time dispatch of both energy systems and aims at minimizing the total expected cost. Additionally, two deterministic models, one of an integrated energy system and one that treats the two systems independently, are presented. We utilize a formulation that considers the linepack of the natural gas system, while it results in a tractable mixed-integer linear programming (MILP) model. Our analysis demonstrates the effectiveness of the proposed model in accommodating high shares of renewables and the importance of proper natural gas system modeling in short-term operations to reveal valuable flexibility of the natural gas system. Moreover, we identify the coordination parameters between the two markets and show their impact on the system’s operation and dispatch.

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Coordination of Power and Natural Gas Systems: Convexification Approaches for Linepack Modeling

Utilizing operational flexibility from natural gas networks can foster the integration of uncertain and variable renewable power production. We model a combined power and natural gas dispatch to reveal the maximum potential of linepack, i.e., energy storage in the pipelines, as a source of flexibility for the power system. The natural gas flow dynamics are approximated by a combination of steady-state equations and varying incoming and outgoing flows in the pipelines to account for both natural gas transport and linepack. This steady-state natural gas flow results in a nonlinear and nonconvex formulation. To cope with the computational challenges, we explore convex quadratic relaxations and linear approximations. We propose a novel mixed-integer second-order cone formulation including McCormick relaxations to model the bidirectional natural gas flow accounting for linepack. Flexibility is quantified in terms of system cost compared to a dispatch model that either neglects linepack or assumes infinite storage capability.

Distributed Reconciliation in Day-Ahead Wind Power Forecasting

With increasing renewable energy generation capacities connected to the power grid, a number of decision-making problems require some form of consistency in the forecasts that are being used as input. In everyday words, one expects that the sum of the power generation forecasts for a set of wind farms is equal to the forecast made directly for the power generation of that portfolio. This forecast reconciliation problem has attracted increased attention in the energy forecasting literature over the last few years. Here, we review the state of the art and its applicability to day-ahead forecasting of wind power generation, in the context of spatial reconciliation. After gathering some observations on the properties of the game-theoretical optimal projection reconciliation approach, we propose to readily rethink it in a distributed setup by using the Alternating Direction Method of Multipliers (ADMM). Three case studies are considered for illustrating the interest and performance of the approach, based on simulated data, the National Renewable Energy Laboratory (NREL) Wind Toolkit dataset, and a dataset for a number of geographically distributed wind farms in Sardinia, Italy.
Do unit commitment constraints affect generation expansion planning? A scalable stochastic model

Due to increasing penetration of stochastic renewable energy sources in electric power systems, the need for flexible resources especially from fast-start conventional generation units (e.g., combined cycle gas turbine plants) is growing. The fast-start conventional units are being operated more frequently in order to respond to the variability and uncertainty of stochastic generation. This raises two important technical questions: as it is common in the literature, is it still an appropriate simplification to ignore the operational unit commitment (UC) constraints of conventional units within the generation expansion planning optimization? And if not, which UC constraint impacts most the expansion planning outcomes? To answer these questions, this paper aims at measuring the planning inefficiency (i.e., the underestimation of need for new generation capacity) caused by ignoring each UC constraint. To this purpose, we develop a centralized network-constrained generation expansion planning model incorporating UC constraints. In particular, we model start-up and shut-down costs, minimum production level and hourly ramping limits of conventional units. Wind power production is considered as the only source of uncertainty, and is modeled through a set of scenarios. A two-stage stochastic programming tool is used, whose first stage determines the long-term expansion and short-term UC decisions over different hours of representative days, while the second stage models the real-time operation for accommodating imbalances arising from wind deviation under different scenarios. Since this problem is potentially hard to solve especially with a large number of representative days and scenarios, a multi-cut Benders’ decomposition algorithm is implemented. The well-functioning of the proposed model and the impact of each UC constraint on planning outcomes are evaluated using an extensive numerical study. In our case studies, the exclusion of ramping constraints from planning optimization causes large error and is the most distorting simplification.

Energy Collectives: a Community and Fairness based Approach to Future Electricity Markets

While power system organization has evolved from a hierarchical structure to a more decentralized model, electricity markets are still not up to date with the ongoing transformation towards more consumer-centric economies. As Information and Communication Technologies (ICT) are broadly adopted, they allow prosumers to have a more proactive role in power system operation. This work introduces the concept of energy collectives, as a community-based electricity market structure. We find that when prosumers are allowed to share energy at community level, overall electricity procurement for the community reflects prosumers’ preferences. We show that community members can be influenced by a supervisory third-party in charge of interfacing with the market and system operator and of guaranteeing the collective common agreements. We simulate a number of test cases and we apply typical principles from analysis of communication networks and distributed systems to assess community fairness.
Exogenous Cost Allocation in Peer-to-Peer Electricity Markets

The deployment of distributed energy resources, combined with a more proactive demand side management, is inducing a new paradigm in power system operation and electricity markets. Within a consumer-centric market framework, peer-to-peer approaches have gained substantial interest. Peer-to-peer markets rely on multi-bilateral negotiation among all agents to match supply and demand. These markets can yield a complete mapping of exchanges onto the grid, hence allowing to rethink the sharing of costs related to the use of common infrastructure and services. We propose here to attribute such costs through exogenous network charges in several alternative ways i.e. uniformly, based on the electrical distance between agents and by zones. This variety covers the main grid physical and regulatory configurations. Since attribution mechanisms are defined in an exogenous manner to affect each P2P trade, they eventually shift the market issue to cover the grid exploitation costs. It can even be used to release the stress on the grid when necessary. The interest of our approach is illustrated on a test case using the IEEE 39 bus test system, underlying the impact of attribution mechanisms on trades and grid usage.
Exploring market properties of policy-based reserve procurement for power systems

This paper proposes a market mechanism for co-optimization of energy and reserve procurement in dayahead electricity markets with high shares of renewable energy. The single-stage chance-constrained day-ahead market clearing problem takes uncertain wind in-feed into account, resulting in optimal day-ahead dispatch schedule and an affine participation policy for generators for the real-time reserve provision. Under certain assumptions, the chance-constrained market clearing is reformulated as a quadratic program. Using tools from equilibrium modeling and variational inequalities, we explore the existence and uniqueness of a Nash equilibrium. Under the assumption of perfect competition in the market, we evaluate the satisfaction of desirable market properties, namely cost recovery, revenue adequacy, market efficiency, and incentive compatibility. To illustrate the effectiveness of the proposed market clearing, it is benchmarked against a deterministic cooptimization of energy and reserve procurement. Biased and unbiased out-of-sample simulation results for a power systems test case highlight that the proposed market clearing results in lower expected system operations cost than the deterministic benchmark, without the loss of any desirable market properties.

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Incentive-Compatibility in a Two-Stage Stochastic Electricity Market with High Wind Power Penetration

A major restructuring of electricity markets takes place worldwide, pursuing maximum economic efficiency. In most modern electricity markets, including the widely adapted Locational Marginal Price (LMP) market, efficiency is only guaranteed under the assumption of perfect competition. Moreover, market design is heavily focused on deterministic conventional generation. Electricity markets, though, are vulnerable to strategic behaviors and challenged by the increased penetration of renewable energy generation. In this paper, we cope with the aforementioned bottlenecks by investigating the application of Vickrey-Clarke-Groves (VCG) auction in a twostage stochastic electricity market. The VCG mechanism achieves incentive-compatibility by rewarding market participants for their contribution towards market efficiency, being attractive from both market operation and participants perspectives. Both traditional and VCG market-clearing approaches are explored and compared, investigating as well the impact of increasing wind power penetration. The main shortcoming of VCG, i.e., not ensuring revenue-adequacy, is quantified in terms of market budget imbalance for various levels of wind power penetration. To this end, a novel ex-post budget redistribution scheme is proposed, which achieves to partially recover budget deficit.

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Online matching and preferences in future electricity markets

Electricity markets are to be rethought in view of the context of deployment of distributed energy resources, new enabling technologies and evolving business models. Future market mechanisms should have no barrier to entry, while being scalable and giving the possibility to accommodate asynchronicity. Consequently, we propose here to use online matching algorithms, relying on various types of continuous double auctions. They allow agents to trade electricity forward contracts while expressing preferences and being continuously matched as new orders come. Such markets can accommodate agents and trades of any size and characteristics. We eventually concentrate on naive greedy and pro-rata matching algorithms. A discrete double-auction is used as a benchmark. The double auctions are generalized to account for preferences. A case-study application allows us to discuss the computational properties and optimality of the various approaches. An upper bound on the sub-optimality of online matching algorithms, compared to an offline double auction, is also provided.

A consensus-ADMM approach for strategic generation investment in electricity markets

This paper addresses a multi-stage generation investment problem for a strategic (price-maker) power producer in electricity markets. This problem is exposed to different sources of uncertainty, including short-term operational (e.g., rivals’ offering strategies) and long-term macro (e.g., demand growth) uncertainties. This problem is formulated as a stochastic bilevel optimization problem, which eventually recasts as a large-scale stochastic mixed-integer linear programming (MILP) problem with limited computational tractability. To cope with computational issues, we propose a consensus version of alternating direction method of multipliers (ADMM), which decomposes the original problem by both short- and long-term scenarios. Although the convergence of ADMM to the global solution cannot be generally guaranteed for MILP problems, we introduce two bounds on the optimal solution, allowing for the evaluation of the solution quality over iterations. Our numerical findings show that there is a trade-off between computational time and solution quality.
Active Distribution Grid Management based on Robust AC Optimal Power Flow

Further integration of distributed renewable energy sources in distribution systems requires a paradigm change in grid management by the distribution system operators (DSO). DSOs are currently moving to an operational planning approach based on activating flexibility from distributed energy resources in day/ hour-ahead stages. This paper follows the DSO trends by proposing a methodology for active grid management by which robust optimization is applied to accommodate spatial-temporal uncertainty. The proposed method entails the use of a multi-period AC-OPF, ensuring a reliable solution for the DSO. Wind and PV uncertainty is modeled based on spatial-temporal trajectories, while a convex hull technique to define uncertainty sets for the model is used. A case study based on real generation data allows illustration and discussion of the properties of the model. An important conclusion is that the method allows the DSO to increase system reliability in the real-time operation. However, the computational effort grows with increases in system robustness.

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A local energy market for electricity and hydrogen

The proliferation of distributed energy resources entails efficient market mechanisms in distribution-level networks. This paper establishes a local energy market (LEM) framework in which electricity and hydrogen are traded. Players in the LEM consist of renewable distributed generators (DGs), loads, hydrogen vehicles (HVs), and a hydrogen storage system (HSS) operated by a HSS agent (HSSA). An iterative LEM clearing method is proposed based on the merit order principle. Players submit offers/bids with consideration of their own preferences and profiles according to the utility functions. The decentralized LEM clearing process not only avoids complex calculation induced by centralized decision process, but also preserves players' privacy. Case studies are conducted that demonstrate that the LEM promotes local integration of renewable energy, reduces peak demand, and improves players' utilities. Sensitivity analysis is then implemented to...
discuss the influences on the LEM clearing results of capacities of DGs, Loads, and the HSS, as well as price of hydrogen from the hydrogen station (HS).

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**A Stochastic Market Design With Revenue Adequacy and Cost Recovery by Scenario: Benefits and Costs**
Two desirable properties of electricity market mechanisms include: i) revenue adequacy for the market, and ii) cost recovery for all generators. Previously proposed stochastic market-clearing mechanisms satisfy both properties in expectation only, or satisfy one property by scenario and another in expectation. Consequently, market parties may perceive significant risks from market participation, and therefore be discouraged from making offers or perhaps even investing. We develop a stochastic two-stage market-clearing model including day-ahead and real-time settlements with an energy-only pricing scheme that ensures both properties by scenario. However, this approach is cost-inefficient in general and may sacrifice other desirable market attributes. Undesirable consequences include: one group of participants will have to pay more to ensure that all other participants have their costs covered, and thus their prices will not be equilibrium supporting; and day-ahead and real-time prices are not arbitraged in expectation, although this can be fixed by allowing virtual bidders to arbitrage but at the potential cost of increased market inefficiency. Considering these pros and cons, we propose our model as an appropriate tool for market analysis, and not for clearing actual markets. Numerical results from case studies illustrate the benefits and costs of the proposed stochastic market design.

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Benefits of spatiotemporal modeling 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 spatiotemporal models for wind power generation and obtain full probabilistic forecasts from 15 min to 5 h ahead. Detailed analyses of forecast performances on 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 spatiotemporal model instead of a temporal one to achieve calibrated aggregated forecasts. Furthermore, spatiotemporal 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 not only 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 and for spatiotemporal modeling in general.

Consensus-based Approach to Peer-to-Peer Electricity Markets with Product Differentiation

With the sustained deployment of distributed generation capacities and the more proactive role of consumers, power systems and their operation are drifting away from a conventional top-down hierarchical structure. Electricity market structures, however, have not yet embraced that evolution. Respecting the high-dimensional, distributed and dynamic
nature of modern power systems would translate to designing peer-to-peer markets, or at least to using such a structure in
the background for a bottom-up approach to future electricity markets. A peer-to-peer market structure based on a Multi-
Bilateral Economic Dispatch (MBED) formulation is introduced, allowing for multi-bilateral trading with product
differentiation, for instance based on consumer preferences. Consequently a Relaxed Consensus+Innovation (RCI)
approach is proposed to solve the MBED in fully decentralized manner. A set of realistic case study analyses shows that
such peer-to-peer market structures can effectively reduce externalities on power systems with a limited cost increase
compared to centralized market approaches. Additionally, the RCI solving approach allows for a fully decentralized market
clearing which converges with a negligible optimality gap, with a limited amount of information being shared.

Convex Relaxations and Approximations of Chance-Constrained AC-OPF Problems
This paper deals with the impact of linear approximations for the unknown nonconvex confidence region of chance-
constrained AC optimal power flow problems. Such approximations are required for the formulation of tractable chance
constraints. In this context, we introduce the first formulation of a chance-constrained second-order cone (SOC) OPF. The
proposed formulation provides convergence guarantees due to its convexity, while it demonstrates high computational
efficiency. Combined with an AC feasibility recovery, it is able to identify better solutions than chance-constrained
nonconvex AC-OPF formulations. To the best of our knowledge, this paper is the first to perform a rigorous analysis of the
AC feasibility recovery procedures for robust SOC-OPF problems. We identify the issues that arise from the linear
approximations, and by using a reformulation of the quadratic chance constraints, we introduce new parameters able to
reshape the approximation of the confidence region. We demonstrate our method on the IEEE 118-bus system.
Correlation-constrained and sparsity-controlled vector autoregressive model for spatio-temporal wind power forecasting

The ever-increasing number of wind farms has brought both challenges and opportunities in the development of wind power forecasting techniques to take advantage of interdependencies between thousands of spatially distributed wind farms, e.g., over a region. In this paper, a Sparsity-Controlled Vector Autoregressive (SC-VAR) model is introduced to obtain sparse model structures in a spatio-temporal wind power forecasting framework by reformulating the original VAR model into a constrained Mixed Integer Non-Linear Programming (MINLP) problem. It allows controlling the sparsity of the coefficient matrices in a direct manner. However, this original SC-VAR is difficult to implement due to its complicated constraints and the lack of guidelines for setting its parameters. To reduce the complexity of this MINLP and to make it possible to incorporate prior expert knowledge to benefit model building and forecasting, the original SC-VAR is modified and a Correlation-Constrained SC-VAR (CCSC-VAR) is proposed based on spatial correlation information about wind farms. Our approach is evaluated based on a case study of very-short-term forecasting for 25 wind farms in Denmark. Comparison is performed with a set of traditional local methods and spatio-temporal methods. The results obtained show the proposed CCSC-VAR has better overall performance than both the original SC-VAR and other benchmark methods, taking into account all evaluation indicators, including sparsity control ability, sparsity, accuracy and efficiency.

Cost-Optimal ATCs in Zonal Electricity Markets

In contrast to existing frameworks for Available Transfer Capacity (ATC) determination, we propose to define ATCs in an integrated and data-driven manner, optimizing for expected operational costs of the whole system to derive cost-optimal ATCs. These ATCs are purely financial parameters, separate from the physical ATCs based on security indices only typically used in zonal electricity markets today. Determining cost-optimal ATCs requires viewing ATCs as an endogenous market construct, and leads naturally to the definition of a market entity whose responsibility is to optimize ATCs. The optimization problem which this entity solves is a stochastic bilevel problem, which we decompose to yield a
computationally tractable formulation. We show that cost-optimal ATCs depend non-trivially on the underlying network structure, and the problem of finding a set of cost-optimal ATCs is in general non-convex. On a European scale test system, cost-optimal ATCs achieve expected total costs midway between those for non-integrated ATCs and a fully stochastic nodal setup. This benefit comes from qualitatively different ATCs compared to typical definitions, with ATCs which exceed the physical cross-border capacity by a factor of 2 or more, and ATCs which are zero between well-connected areas. Our results indicate that the perceived efficiency gap between zonal and nodal markets may be exaggerated if non-optimal ATCs are used.

**Data-driven Security-Constrained AC-OPF for Operations and Markets**

In this paper, we propose a data-driven preventive security-constrained AC optimal power flow (SC-OPF), which ensures small-signal stability and N-1 security. Our approach can be used by both system and market operators for optimizing redispatch or AC based market-clearing auctions. We derive decision trees from large datasets of operating points, which capture all security requirements and allow to define tractable decision rules that are implemented in the SC-OPF using mixed-integer nonlinear programming (MINLP). We propose a second-order cone relaxation for the non-convex MINLP, which allows us to translate the non-convex and possibly disjoint feasible space of secure system operation to a convex mixed-integer OPF formulation. Our case study shows that the proposed approach increases the feasible space represented in the SC-OPF compared to conventional methods, can identify the global optimum as opposed to tested MINLP solvers and significantly reduces computation time due to a decreased problem size.
Ellipsoidal prediction regions for multivariate uncertainty characterization

While substantial advances are observed in probabilistic forecasting for power system operation and electricity market applications, most approaches are still developed in a univariate framework. This prevents from informing about the interdependence structure among locations, lead times and variables of interest. Such dependencies are key in a large share of operational problems involving renewable power generation and electricity prices for instance. The few methods that account for dependencies translate to sampling scenarios based on given marginals and dependence structures. However, for classes of decision-making problems based on robust, interval chance-constrained optimization, necessary inputs take the form of multivariate prediction regions rather than scenarios. The current literature is at very primitive stage of characterizing multivariate prediction regions to be employed in these classes of optimization problems. To address this issue, we introduce a new class of multivariate forecasts which form as multivariate ellipsoids for non-Gaussian variables. We propose a data-driven systematic framework to readily generate and evaluate ellipsoidal prediction regions, with predefined probability guarantees and minimum conservativeness. A skill score is proposed for quantitative assessment of the quality of prediction ellipsoids. A set of experiments is used to illustrate the discrimination ability of the proposed scoring rule for potential misspecification of ellipsoidal prediction regions. Application results based on three datasets with wind, PV power and electricity prices, allow us to assess the skill of the resulting ellipsoidal prediction regions, in terms of calibration, sharpness and overall skill.

Negotiation Algorithms for Peer-to-Peer Electricity Markets: Computational Properties

Building on the concepts of transactive energy and consumer-centric electricity markets, the interest in community based and peer-to-peer structures to energy transactions and management has substantially increased over the last few years. However, several computational challenges are to be tackled in order for these approaches to be deployed in real-world applications. Our aim here is to identify and analyze these challenges, by comparing distributed community-based market approaches to decentralized and distributed versions of peer-to-peer electricity markets. We show convergence trends of the investigated algorithms as well as how they respond to larger number of participants and presence of asynchronicities. Our findings highlight the practical challenges to face with these setups, in particular with peer-to-peer markets, justified by the further proposal of hybrid approaches and of sparsification of negotiation processes.
Offering Strategy of a Flexibility Aggregator in a Balancing Market Using Asymmetric Block Offers

In order to enable large-scale penetration of renewables with variable generation, new sources of flexibility have to be exploited in the power systems. Allowing asymmetric block offers (including response and rebound blocks) in balancing markets can facilitate the participation of flexibility aggregators and unlock load-shifting flexibility from, e.g., thermostatic loads. In this paper, we formulate an optimal offering strategy for a risk-averse flexibility aggregator participating in such a market. Using a price-taker approach, load flexibility characteristics and balancing market price forecast scenarios are used to find optimal load-shifting offers under uncertainty. The problem is formulated as a stochastic mixed-integer linear program and can be solved with reasonable computational time. This work is taking place in the framework of the real-life demonstration project EcoGrid 2.0, which includes the operation of a balancing market on the island of Bornholm, Denmark. In this context, aggregators will participate in the market by applying the offering strategy optimization tool presented in this paper.

Optimal Offering Strategy of an EV Aggregator in the Frequency-Controlled Normal Operation Reserve Market

Electric vehicles (EVs) are to play an important role in electricity markets, since their energy storage capability can be beneficial to power systems operation. Electric vehicle aggregators will consequently develop adequate offering strategies to participate in energy and reserve markets, accounting for the market rules and operational capabilities of EVs aggregators (e.g., fleet of EVs). In this paper, we propose an offering strategy model for an EV aggregator to participate in the frequency-controlled normal operation reserve service (FCR-N) in Eastern Denmark. The aim is to maximize the expected revenue of the aggregator, accounting for potential penalties for missing the provision of both upward and downward reserves. The methodology has been modeled and tested under the scope of the PARKER project, which considers a case study based on real data from a small fleet of electric vehicles. An important conclusion relates to the
Polyhedral Predictive Regions for Power System Applications
Despite substantial improvement in the development of forecasting approaches, conditional and dynamic uncertainty estimates ought to be accommodated in decision-making in power system operation and market, in order to yield either cost-optimal decisions in expectation, or decision with probabilistic guarantees. The representation of uncertainty serves as an interface between forecasting and decision-making problems, with different approaches handling various objects and their parameterization as input. Following substantial developments based on scenario-based stochastic methods, robust and chance-constrained optimization approaches have gained increasing attention. These often rely on polyhedra as a representation of the convex envelope of uncertainty. In the work, we aim to bridge the gap between the probabilistic forecasting literature and such optimization approaches by generating forecasts in the form of polyhedra with probabilistic guarantees. For that, we see polyhedra as parameterized objects under alternative definitions (under $L_1$ and $L_\infty$ norms), the parameters of which may be modelled and predicted. We additionally discuss assessing the predictive skill of such multivariate probabilistic forecasts. An application and related empirical investigation results allow us to verify probabilistic calibration and predictive skills of our polyhedra.

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Polyhedral Predictive Regions for Power System Applications
Despite substantial improvement in the development of forecasting approaches, conditional and dynamic uncertainty estimates ought to be accommodated in decision-making in power system operation and market, in order to yield either cost-optimal decisions in expectation, or decision with probabilistic guarantees. The representation of uncertainty serves as an interface between forecasting and decision-making problems, with different approaches handling various objects and their parameterization as input. Following substantial developments based on scenario-based stochastic methods, robust and chance-constrained optimization approaches have gained increasing attention. These often rely on polyhedra as a representation of the convex envelope of uncertainty. In the work, we aim to bridge the gap between the probabilistic forecasting literature and such optimization approaches by generating forecasts in the form of polyhedra with probabilistic guarantees. For that, we see polyhedra as parameterized objects under alternative definitions (under $L_1$ and $L_\infty$ norms), the parameters of which may be modelled and predicted. We additionally discuss assessing the predictive skill of such multivariate probabilistic forecasts. An application and related empirical investigation results allow us to verify probabilistic calibration and predictive skills of our polyhedra.
Prévision météorologique pour les énergies renouvelables
Solar and wind power are the renewable energy sectors with the highest worldwide growth in installed capacity. However, their productions vary instantly with the weather situation. This variability is an issue to increase their use in an electricity network and a consumption park originally designed to accommodate energy with relatively stable and controllable production. Meteorological forecasts of wind and solar irradiance are solutions for managing this variability and contributing to an energy transition towards less fossil energies.

Price-Taker Offering Strategy in Electricity Pay-as-Bid Markets
The recent increase in the deployment of renewable energy sources may affect the offering strategy of conventional producers, mainly in the balancing market. The topics of optimal offering strategy and self-scheduling of thermal units have been extensively addressed in the literature. The feasible operating region of such units can be modeled using a mixed-integer linear programming approach, and the trading problem as a linear programming problem. However, the existing models mostly assume a uniform pricing scheme in all market stages, while several European balancing markets (e.g., in Germany and Italy) are settled under a pay-as-bid pricing scheme. The existing tools for solving the trading problem in pay-as-bid electricity markets rely on non-linear optimization models, which, combined with the unit commitment constraints, result in a mixed-integer non-linear programming problem. In contrast, we provide a linear formulation for that trading problem. Then, we extend the proposed approach by formulating a two-stage stochastic problem for optimal offering in a two-settlement electricity market with a pay-as-bid pricing scheme at the balancing stage. The resulting model is mixed-integer and linear. The proposed model is tested on a realistic case study against a sequential offering approach, showing the capability of increasing profits in expectation.
Smart grids innovation challenge

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Visualizing big energy data
Visualization is a crucial component of data analysis. It is always a good idea to plot the data before fitting models, making predictions, or drawing conclusions. As sensors of the electric grid are collecting large volumes of data from various sources, power industry professionals are facing the challenge of visualizing such data in a timely fashion. In this article, we demonstrate several data-visualization solutions for big energy data through three case studies involving smart-meter data, phasor measurement unit (PMU) data, and probabilistic forecasts, respectively.

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A Bayesian inference approach to unveil supply curves in electricity markets

With increased competition in wholesale electricity markets, the need for new decision-making tools for strategic producers has arisen. Optimal bidding strategies have traditionally been modeled as stochastic profit maximization problems. However, for producers with non-negligible market power, modeling the interactions with rival participants is fundamental. This can be achieved through equilibrium and hierarchical optimization models. The efficiency of these methods relies on the strategic producer’s ability to model rival participants’ behavior and supply curve. But a substantial gap remains in the literature on modeling this uncertainty. In this study we introduce a Bayesian inference approach to reveal the aggregate supply curve in a day-ahead electricity market. The proposed algorithm relies on Markov Chain Monte Carlo and Sequential Monte Carlo methods. The major appeal of this approach is that it provides a complete model of the uncertainty of the aggregate supply curve, through an estimate of its posterior distribution. We show on a small case study that we are able to reveal accurately the aggregate supply curve with no prior information on rival participants. Finally we show how this piece of information can be used by a price-maker producer in order to devise an optimal bidding strategy.

Attribution mechanisms for ancillary service costs induced by variability in power delivery

The increased penetration of renewable energy sources in existing power systems has led to necessary developments in electricity market mechanisms. Most importantly, renewable energy generation is increasingly made accountable for deviations between scheduled and actual energy generation. However, there is no mechanism to enforce accountability for the additional costs induced by power fluctuations. These costs are socialized and eventually supported by electricity customers. We propose some metrics for assessing the contribution of all market participants to power regulation needs, as well as an attribution mechanism for fairly redistributing related power regulation costs. We discuss the effect of various metrics used by the attribution mechanisms, and we illustrate, in a game-theoretical framework, their consequences on the
strategic behavior of market participants. We also illustrate, by using the case of Western Denmark, how these mechanisms may affect revenues and the various market participants.

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**Coordinating Flexibility under Uncertainty in Multi-Area AC and DC Grids**

In the future, mixed AC and DC grids, spanning multiple areas operated by different transmission system operators (TSO), are expected to offer the necessary controllability for integrating large amounts of intermittent renewable generation. This is facilitated by high voltage direct current transmission based on voltage source converter technology that can offer recourse actions in the form of preventive and corrective control of both active and reactive power. Market-clearing procedures, based on optimal power flow algorithms, need to be revised to account for DC transmission, flexibility and privacy requirements. To this end, we propose a decentralized two-stage stochastic market-clearing algorithm that incorporates meshed DC grids and allows the sharing of flexibility resources between areas. The benefit of this approach lies in its pricing mechanism, used for coordinating the different area subproblems and requiring only a moderate exchange of information while ensuring system-wide optimality. Case studies are presented to illustrate the methodology and to demonstrated the benefits of additional controllability provided by DC grids.

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Data-driven Demand Response Characterization and Quantification
Analysis of load behavior in demand response (DR) schemes is important to evaluate the performance of participants. Very few real-world experiments have been carried out and quantification and characterization of the response is a difficult task. Nevertheless it will be a necessary tool for portfolio management of consumers in a DR framework. In this paper we develop methods to quantify and characterize the amount of DR in a load. The contribution to the aggregated load from each household is quantified on a daily basis, showing the potential variability of the response in time. Clustering on the average values and standard deviation of the contribution regroups households with the same average response. Independent Component Analysis (ICA) is used to characterize different DR delivery profiles.

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Data-Driven Security-Constrained OPF
In this paper we unify electricity market operations with power system security considerations. Using data-driven techniques, we address both small signal stability and steady-state security, derive tractable decision rules in the form of line flow limits, and incorporate the resulting constraints in market clearing algorithms. Our goal is to minimize redispatching actions, and instead allow the market to determine the most cost-efficient dispatch while considering all security constraints. To maintain tractability of our approach we perform our security assessment offline, examining large datasets, both from measurements and simulations, in order to determine stable and unstable operating regions. With the help of decision trees, we transform this information to linear decision rules for line flow constraints. We propose conditional line transfer limits, which can accurately capture security considerations, while being less conservative than current approaches. Our approach can be scalable for large systems, accounts explicitly for power system security, and enables the electricity market to identify a cost-efficient dispatch avoiding redispatching actions. We demonstrate the performance of our method in a case study.

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Decision support program for congestion management using demand side flexibility

In the past decades, Distribution System Operators (DSOs) have been mitigating distribution networks (DNs) contingencies by opting to grid reinforcements. However, this approach is not always cost and time efficient. Demand Side Flexibility (DSF) is one of the recent alternatives used in DNs congestion management. Consequently, new market players such as aggregators are needed to handle DSF transaction between customers and DSOs. This paper proposes and models a decision support program (DSP) to optimize the total cost charged by the DSO for using DSF services. Moreover, the energy rebound effect is taken into consideration as well as the uncertain behavior of customers. Finally, the distribution grid of the Danish Bornholm Island is used to illustrate the merits of the DSP. The total cost incurred by the DSO is calculated and presented.

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Demand response evaluation and forecasting — Methods and results from the EcoGrid EU experiment

Understanding electricity consumers participating in new demand response schemes is important for investment decisions and the design and operation of electricity markets. Important metrics include peak response, time to peak response, energy delivered, ramping, and how the response changes with respect to external conditions. Such characteristics dictate the services DR is capable of offering, like primary frequency reserves, peak load shaving, and system balancing. In this paper, we develop methods to characterise price-responsive demand from the EcoGrid EU demonstration in a way that was bid into a real-time market. EcoGrid EU is a smart grid experiment with 1900 residential customers who are equipped with smart meters and automated devices reacting to five-minute electricity pricing. Customers are grouped and analysed according to the manufacturer that controlled devices. A number of advanced statistical models are used to show significant flexibility in the load, peaking at 27% for the best performing groups.

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Exploiting Flexibility in Coupled Electricity and Natural Gas Markets: A Price-Based Approach

Natural gas-fired power plants (NGFPs) are considered a highly flexible component of the energy system and can facilitate the large-scale integration of intermittent renewable generation. Therefore, it is necessary to improve the coordination between electric power and natural gas systems. Considering a market-based coupling of these systems, we introduce a decision support tool that increases market efficiency in the current setup where day-ahead and balancing markets are cleared sequentially. The proposed approach relies on the optimal adjustment of natural gas price to modify the scheduling of power plants and reveals the necessary flexibility to handle stochastic renewable production. An essential property of this price-based approach is that it guarantees no financial imbalance (deficit or surplus) for the system operator at the day-ahead stage. Our analysis shows that the proposed mechanism reduces the expected system cost and efficiently accommodates high shares of renewables.

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Guest Editorial - Special Section on Emerging Informatics for Risk Hedging and Decision Making in Smart Grids

The development of smart grids worldwide aims at tackling various challenges facing power system operation and planning due to increased penetration of many new technologies of diversified properties. On the one hand, system operators and many other participants have to deal with increased uncertainties and risks involved in daily operation and planning activities. On the other hand, applications of many new metering and measurement devices, capable of closely monitoring and sensing grid operation in real time, result in overwhelming amount of measurement data of high precision and resolution. By far, how to make the best use of the massive data remains quite a challenging task facing power system researchers and practitioners [1].

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Impact of Public Aggregate Wind Forecasts on Electricity Market Outcomes

Following a call to foster a transparent and more competitive market, member states of the European transmission system operator are required to publish, among other information, aggregate wind power forecasts. The publication of the latter information is expected to benefit market participants by offering better knowledge of the market operation, leading subsequently to a more competitive energy market. Driven by the above regulation, we consider an equilibrium study to address how public information of aggregate wind power forecasts can potentially affect market results, social welfare as well as the profits of participating power producers. We investigate, therefore, a joint day-ahead energy and reserve auction, where producers offer their conventional power strategically based on a complementarity approach and their wind power at generation cost based on a forecast. In parallel, an iterative game-theoretic approach (diagonalization) is incorporated in order to investigate the existence of an equilibrium for various values of aggregate forecast. As anticipated, variations in public forecasts will affect market results and, more precisely, under-forecasts can mislead power producers to make decisions that favor social welfare, while over-forecasts will cause the opposite effect. Furthermore, energy and reserve market prices can also be affected by deviations in aggregate wind forecasts altering, inevitably, the profits of all power producers.

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Modeling the transient security constraints of natural gas network in day-ahead power system scheduling

The rapid deployment of gas-fired generating units makes the power system more vulnerable to failures in the natural gas system. To reduce the risk of gas system failure and to guarantee the security of power system operation, it is necessary to take the security constraints of natural gas pipelines into account in the day-ahead power generation scheduling model. However, the minute- and hour-level dynamic characteristics of gas systems prevents an accurate decision-making simply with the steady-state gas flow model. Although the partial differential equations depict the dynamics of gas flow accurately, they hard to be embedded into the power system scheduling model, which consists of algebraic equations and inequalities. This paper addresses this dilemma by proposing an algebraic transient model of natural gas network which is similar to the branch-node model of power network. Based on the gas flow model, the day-ahead power system scheduling model is then proposed with the solution technique of successive linear programming and Benders decomposition. Tests are conducted to prove the effectiveness of the proposed models.

Offering strategy of a price-maker energy storage system in day-ahead and balancing markets

Energy storage systems (ESS) are considered as a promising solution to improve power system flexibility and facilitate the integration of renewables in electricity markets. This paper investigates the impact of strategic offering by an ESS operator in the day-ahead and balancing market. The offering strategy of a price-maker ESS operator is formulated as a bilevel model, where the upper-level problem represents the profit maximization of the ESS operator and the lower-level problem simulates the market clearing outcome. This methodological framework can be used either to assess market efficiency distortion or as a trading strategy from the perspective of the ESS operator. Our analysis shows that adopting strategic behavior may improve ESS expected profit but reduces social welfare, especially for high ESS energy-to-power ratios.
Optimal offering and allocation policies for wind power in energy and reserve markets

Proliferation of wind power generation is increasingly making this power source an important asset in designs of energy and reserve markets. Intuitively, wind power producers will require the development of new offering strategies that maximize the expected profit in both energy and reserve markets while fulfilling the market rules and its operational limits. In this paper, we implement and exploit the controllability of the proportional control strategy. This strategy allows the splitting of potentially available wind power generation in energy and reserve markets. In addition, we take advantage of better forecast information from the different day-ahead and balancing stages, allowing different shares of energy and reserve in both stages. Under these assumptions, different mathematical methods able to deal with the uncertain nature of wind power generation, namely, stochastic programming, with McCormick relaxation and piecewise linear decision rules are adapted and tested aiming to maximize the expected revenue for participating in both energy and reserve markets, while accounting for estimated balancing costs for failing to provide energy and reserve. A set of numerical examples, as well as a case study based on real data, allow the analysis and evaluation of the performance and behavior of such techniques. An important conclusion is that the use of the proposed approaches offers a degree of freedom in terms of minimizing balancing costs for the wind power producer strategically to participate in both energy and reserve markets.

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Optimal Offering and Operating Strategy for a Large Wind-Storage System as a Price Maker

Wind farms and energy storage systems are playing increasingly more important roles in power systems, which makes their offering non-negligible in some markets. From the perspective of wind farm-energy storage systems (WF-ESS), this paper proposes an integrated strategy of day-ahead offering and real-time operation policies to maximize their overall profit. As participants with large capacity in electricity markets can influence cleared prices by strategic offering, a large scaled WFESS is assumed to be a price maker in day-ahead markets. Correspondingly, the strategy considers influence of offering quantity on cleared day-ahead prices, and adopts linear decision rules as the real time control strategy. These allow enhancing overall profits from both day-ahead and balancing markets. The integrated price-maker strategy is formulated as a stochastic programming problem, where uncertainty of wind power generation and balancing prices are taken into account in the form of scenario sets, permitting to reformulate the optimization problem as a linear program. Case studies validate the effectiveness of the proposed strategy by highlighting and quantifying benefits comparing with the price-taker strategy, and also show the profit enhancement brought to the distributed resources.

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In this paper, a mathematical approach for the optimal planning of integrated energy systems is proposed. In order to address the challenges of future, RES-dominated energy systems, the model deliberates between the expansion of traditional energy infrastructures, the integration of these infrastructures using conversion technologies (e.g. gas-to-electricity-and-heat, power-to-heat, power-to-gas), and the placement of energy storage. The model is demonstrated using a representative case study from the city of Eindhoven. Current energy data from 2015 is combined with city development scenarios and sustainability goals for 2030 and 2045. Optimal green- and brownfield designs for a district’s future integrated energy system are compared using a one-step, as well as a two-step planning approach. As expected, the greenfield designs are more cost efficient, as their results are not constrained by the existing infrastructure.
The upper-level (UL) problem is to maximize the PDISCO’s profit, while the lower-level (LL) problem indicates the profit maximization per DGO. Since the UL problem is non-linear and non-convex and the LL problems are linear and convex, we reformulate the proposed model to a solvable mathematical program with equilibrium constraints (MPEC) by an equivalent primal-dual approach. The numerical results of the case studies show the effectiveness and scalability of the proposed model.

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Keywords: Distributed generation (DG), Proactive distribution company (PDISCO), Distributed generation owner (DGO), Bayesian game, Bilevel model, Multi-period AC power flow, Mathematical program with equilibrium constraints (MPEC), AC power flow
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Research output: Contribution to journal › Journal article – Annual report year: 2018 › Research › peer-review

**RE-Europe, a large-scale dataset for modeling a highly renewable European electricity system**

Future highly renewable energy systems will couple to complex weather and climate dynamics. This coupling is generally not captured in detail by the open models developed in the power and energy system communities, where such open models exist. To enable modeling such a future energy system, we describe a dedicated large-scale dataset for a renewable electric power system. The dataset combines a transmission network model, as well as information for generation and demand. Generation includes conventional generators with their technical and economic characteristics, as well as weather-driven forecasts and corresponding realizations for renewable energy generation for a period of 3 years. These may be scaled according to the envisioned degrees of renewable penetration in a future European energy system. The spatial coverage, completeness and resolution of this dataset, open the door to the evaluation, scaling analysis and replicability check of a wealth of proposals in, e.g., market design, network actor coordination and forecasting of renewable power generation.

**General information**

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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy System Management, Energy Analytics and Markets
Contributors: Jensen, T. V., Pinson, P.
Number of pages: 31
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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.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Statistics and Data Analysis, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Contributors: Lenzi, A., Pinson, P., Clemmensen, L. K. H., Guillot, G.
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Web of Science (2017): Indexed yes
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10.1007/s00477-016-1329-0
Towards fully renewable energy systems - Experience and trends in Denmark

Deployment of renewable energy generation capacities and integration of their power production into existing power systems has become a global trend throughout the world, with a common set of operational challenges stemming from variability and limited predictability of power generation from, e.g., wind and solar. Denmark is a country that invested early in wind energy, rapidly proposing very ambitious goals for the future of its energy system and global energy usage. While the case of Denmark is specific due to its limited size and good interconnections, there may still be a lot to learn from the way operational practice has evolved, also shifting towards a liberalized electricity market environment, and more generally going along with other technological and societal evolution. Our aim here is to give an overview of recent and current initiatives in Denmark which contribute towards a goal of reaching a fully renewable energy system.

General information
Publication status: Published
Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Contributors: Pinson, P., Mitridati, L. M. M., Ordoudis, C., Østergaard, J.
Pages: 26 - 35
Publication date: 2017
Peer-reviewed: Yes
以用户为中心的新兴电力市场模式

随着可再生能源在现代能源产业中的占比不断提高，其对现行电力系统和电力市场的运行机制所带来的影响也日趋明显；同时，通过与数字信息产业深度结合，分布式能量管理手段也处于飞速发展阶段。在这二者的驱动下，一种以用户为中心的新兴电力市场模式正以不同的表现形式出现在世界各地。文章以高度概括的方式介绍了这一新兴电力市场模式，浅析了其在不同表现形式下的机理和特征。基于这一新兴电力市场模式在短期内所取得的发展成就，有理由相信此类新兴电力市场模式将逐步成为未来电力市场中的重要组成部分。

Accountability for Uncertainty in Electricity Markets

General information
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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Contributors: Papakonstantinou, A., Pinson, P.
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Publication date: 2016
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iaee16_bergen_ext_v2.pdf
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Source: PublicationPreSubmission
Source ID: 124337825
Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2016 › Research › peer-review
Adaptive robust polynomial regression for power curve modeling with application to wind power forecasting

Wind farm power curve modeling, which characterizes the relationship between meteorological variables and power production, is a crucial procedure for wind power forecasting. In many cases, power curve modeling is more impacted by the limited quality of input data rather than the stochastic nature of the energy conversion process. Such nature may be due the varying wind conditions, aging and state of the turbines, etc. And, an equivalent steady-state power curve, estimated under normal operating conditions with the intention to filter abnormal data, is not sufficient to solve the problem because of the lack of time adaptivity. In this paper, a refined local polynomial regression algorithm is proposed to yield an adaptive robust model of the time-varying scattered power curve for forecasting applications. The time adaptivity of the algorithm is considered with a new data-driven bandwidth selection method, which is a combination of pilot estimation based on blockwise least-squares parabolic fitting and the probability integral transform. The regression model is then extended to a more robust one, in which a new dynamic forgetting factor is defined to make the estimator forget the out-of-date data swiftly and also achieve a better trade-off between robustness against noisy data and time adaptivity. A case study based on a real-world dataset validates the properties of the proposed regression method. Results show that the new method could flexibly respond to abnormal data at different lead times and has better performance than common benchmarks for short-term forecasting.

General information
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Organisations: Department of Applied Mathematics and Computer Science, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Tsinghua University
Contributors: Xu, M., Pinson, P., Lu, Z., Qiao, Y., Min, Y.
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General information
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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Ordoudis, C., Pinson, P., Morales González, J. M., Zugno, M.
Number of pages: 5
Publication date: 2016

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SingleAreaRTS96
Research output: Book/Report › Report – Annual report year: 2016 › Research › peer-review
A Robust Optimisation Approach using CVaR for Unit Commitment in a Market with Probabilistic Offers

The large scale integration of renewable energy sources (RES) challenges power system planners and operators alike as it can potentially introduce the need for costly investments in infrastructure. Furthermore, traditional market clearing mechanisms are no longer optimal due to the stochastic nature of RES. This paper presents a risk-aware market clearing strategy for a network with significant shares of RES. We propose an electricity market that embeds the uncertainty brought by wind power and other stochastic renewable sources by accepting probabilistic offers and use a risk measure defined by conditional value-at-risk (CVaR) to evaluate the risk of high re-dispatching cost due to the mis-estimation of renewable energy. The proposed model is simulated on a 39-bus network, whereby it is shown that significant reductions can be achieved by properly managing the risks of mis-estimation of stochastic generation.

General information
Publication status: Published
Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, University of Strathclyde
Contributors: Bukhsh, W. A., Papakonstantinou, A., Pinson, P.
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Source: PublicationPreSubmission
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2016 › Research › peer-review

Demand Forecasting at Low Aggregation Levels using Factored Conditional Restricted Boltzmann Machine.
The electrical demand forecasting problem can be regarded as a nonlinear time series prediction problem depending on many complex factors since it is required at various aggregation levels and at high temporal resolution. To solve this challenging problem, various time series and machine learning approaches have been proposed in the literature. As an evolution of neural network-based prediction methods, deep learning techniques are expected to increase the prediction accuracy by allowing stochastic formulations and bi-directional connections between neurons. In this paper, we investigate a newly developed deep learning model for time series prediction, namely Factored Conditional Restricted Boltzmann Machine (FCRBM), and extend it for electrical demand forecasting. The assessment is made on the EcoGrid dataset, originating from the Bornholm island experiment in Denmark, consisting of aggregated electric power consumption, local price and meteorological data collected from 1900 customers. The households are equipped with local generation and smart appliances capable of responding to realtime pricing signals. The results show that for the short-term (5 minute to 1 day ahead) prediction problems solved here, FCRBM outperforms the benchmark machine learning approach, i.e. Support Vector Machine

General information
Publication status: Published
Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Eindhoven University of Technology
Effects of Risk Aversion on Market Outcomes: A Stochastic Two-Stage Equilibrium Model

This paper evaluates how different risk preferences of electricity producers alter the market-clearing outcomes. Toward this goal, we propose a stochastic equilibrium model for electricity markets with two settlements, i.e., day-ahead and balancing, in which a number of conventional and stochastic renewable (e.g., wind power) producers compete. We assume that all producers are price-taking and can be risk-averse, while loads are inelastic to price. Renewable power production is the only source of uncertainty considered. The risk of profit variability of each producer is incorporated into the model using the conditional value-at-risk (CVaR) metric. The proposed equilibrium model consists of several risk-constrained profit maximization problems (one per producer), several curtailment cost minimization problems (one per load), and power balance constraints. Each optimization problem is then replaced by its optimality conditions, resulting in a mixed complementarity problem. Numerical results from a case study based on the IEEE one-area reliability test system are derived and discussed.

Evaluating price-based demand response in practice – with application to the EcoGrid EU Experiment

Increased emphasis is placed today on various types of demand response, motivated by the integration of renewable energy generation and efficiency improvements in electricity markets. Some advocated for the development of price-based approaches, where the conditional dynamic elasticity of final users is exploited in the power system, e.g., for system balancing. However, very few real-world experiments have been carried out and price-based demand response has consistently been found difficult to assess and quantify. It is our aim here to describe an approach to do so, as motivated by the large-scale EcoGrid EU experiment. In this project, 1900 houses were equipped with smart meters and other automation devices in order to adapt consumption to real-time electricity prices every five minutes, while monitoring it with the same resolution. Our approach first relies on the clustering of residential load observations that behave similarly within a given experiment. Then, a clinical testing approach, based on a test and a control group, is adapted to assess whether price-responsive loads were actually responsive or not. Interestingly, in the deployment phase of the project, the results show that houses could be deemed price-responsive on some test days, while results were inconclusive on some others.
Generation and evaluation of space-Time trajectories of photovoltaic power

In the probabilistic energy forecasting literature, emphasis is mainly placed on deriving marginal predictive densities for which each random variable is dealt with individually. Such marginals description is sufficient for power systems related operational problems if and only if optimal decisions are to be made for each lead-time and each location independently of each other. However, many of these operational processes are temporally and spatially coupled, while uncertainty in photovoltaic (PV) generation is strongly dependent in time and in space. This issue is addressed here by analysing and capturing spatio-temporal dependencies in PV generation. Multivariate predictive distributions are modelled and space-time trajectories describing the potential evolution of forecast errors through successive lead-times and locations are generated. Discrimination ability of the relevant scoring rules on performance assessment of space-time trajectories of PV generation is also studied. Finally, the advantage of taking into account space-time correlations over probabilistic and point forecasts is investigated. The empirical investigation is based on the solar PV dataset of the Global Energy Forecasting Competition (GEFCom) 2014.

General information
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Contributors: Golestaneh, F., Gooi, H. B., Pinson, P.
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Web of Science (2016): Impact factor 7.182
Web of Science (2016): Indexed yes
Original language: English
Generation Expansion Planning with Large Amounts of Wind Power via Decision-Dependent Stochastic Programming

Power generation expansion planning needs to deal with future uncertainties carefully, given that the invested generation assets will be in operation for a long time. Many stochastic programming models have been proposed to tackle this challenge. However, most previous works assume predetermined future uncertainties (i.e., fixed random outcomes with given probabilities). In several recent studies of generation assets' planning (e.g., thermal versus renewable), new findings show that the investment decisions could affect the future uncertainties as well. To this end, this paper proposes a multistage, decision-dependent stochastic optimization model for long-term, largescale generation expansion planning where large amounts of wind power are involved. In the decision-dependent model, the future uncertainties are not only affecting but also affected by the current decisions. In particular, the probability distribution function is determined by not only input parameters but also decision variables. To deal with the nonlinear constraints in our model, a quasi-exact solution approach is then introduced to reformulate the multistage stochastic investment model to a mixed-integer linear programming (MILP) model. The wind penetration, investment decisions, and the optimality of the decision-dependent model are evaluated in a series of multistage case studies. The results show that the proposed decision-dependent model provides effective optimization solutions for long-term generation expansion planning.

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Organisations: Department of Electrical Engineering, Energy Analytics and Markets, University of Central Florida, Argonne National Laboratory
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Keywords: Decision-Dependent, Stochastic, Wind, Mixed Integer Programming, Power Generation, Expansion Planning, Long-term, Endogenous Uncertainties

Generation of scenarios from calibrated ensemble forecasts with a dual ensemble copula coupling approach

Probabilistic forecasts in the form of ensemble of scenarios are required for complex decision making processes. Ensemble forecasting systems provide such products but the spatio-temporal structures of the forecast uncertainty is lost when statistical calibration of the ensemble forecasts is applied for each lead time and location independently. Non-parametric approaches allow the reconstruction of spatio-temporal joint probability distributions at a low computational cost. For example, the ensemble copula coupling (ECC) method rebuilds the multivariate aspect of the forecast from the original ensemble forecasts. Based on the assumption of error stationarity, parametric methods aim to fully describe the forecast dependence structures. In this study, the concept of ECC is combined with past data statistics in order to account for the autocorrelation of the forecast error. The new approach, called d-ECC, is applied to wind forecasts from the high resolution ensemble system COSMO-DE-EPS run operationally at the German weather service. Scenarios generated by
ECC and d-ECC are compared and assessed in the form of time series by means of multivariate verification tools and in a product oriented framework. Verification results over a 3 month period show that the innovative method d-ECC outperforms or performs as well as ECC in all investigated aspects.

General information
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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, University of Bonn, Deutscher Wetterdienst
Contributors: Ben Bouallègue, Z., Heppelmann, T., Theis, S. E., Pinson, P.
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Identifying and characterizing the impact of turbine icing on wind farm power generation: Impact of turbine icing on wind farm production
Wind park power production in cold climate regions is significantly impacted by ice growth on turbine blades. This can lead to significant errors in power forecasts and in the estimation of expected power production during turbine siting. A modeling system is presented that uses a statistical modeling approach to estimate the power loss due to icing, using inputs from both a physical icing and a numerical weather prediction model. The physical icing model is that of Davis et al., [1] with updates to the simulation of ice ablation. A new approach for identifying periods of turbine blade icing from power observations was developed and used to calculate the observed power loss caused by icing. The observed icing power loss for 2 years at six wind parks was used to validate the modeling system performance. Production estimates using the final production loss model reduce the root mean squared error when compared with the empirical wind park power curve (without icing influence) at five of the six wind parks while reducing the mean bias at all six wind parks. In addition to performing well when fit to each wind park, the production loss model was shown to improve the estimate of power when fit using all six wind parks, suggesting it may also be useful for wind parks where production data are not available.

General information
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Contributors: Davis, N., Pinson, P., Hahmann, A. N., Clausen, N., Žagar, M.
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Impact of Inter- and Intra-Regional Coordination in Markets With a Large Renewable Component

The establishment of the single European day-ahead market has accomplished a crucial step towards the spatial integration of the European power system. However, this new arrangement does not consider any intra-regional coordination of day-ahead and balancing markets and thus may become counterproductive or inefficient under uncertain supply, e.g., from weather-driven renewable power generation. In the absence of a specific target model for the common balancing market in Europe, we introduce a framework to compare different coordination schemes and market organizations. The proposed models are formulated as stochastic equilibrium problems and compared against an optimal market setup. The simulation results reveal significant efficiency loss in case of partial coordination and diversity of market structure among regional power systems.

General information
Publication status: Published
Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Delikaraoglou, S., Morales González, J. M., Pinson, P.
Pages: 5061-5070
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Peer-reviewed: Yes

Impact of Renewable Energy Forecast Imperfections on Market-Clearing Outcomes

The increased integration of renewable energy sources, in particular wind and solar power, calls for changes in power system operation. Current market designs that are only efficient to accommodate limited uncertainty are highly challenged by the partly predictable renewable energy generation. Hence, innovative market structures have been proposed to cope with the uncertainty introduced. Nonetheless, the quality of wind power forecasts may affect the market outcome due to their inaccuracy. For this reason, a framework is proposed to examine market-clearing algorithms, both deterministic and stochastic approaches, under imperfect wind power forecasts in order to quantify their influence on the market outcome. Results show that mean value mismatch between "estimated" and "realized" distributions has the highest impact on total system cost. Finally, it is examined if cost recovery for market players is guaranteed in the presence of inaccurate wind
power forecasts.

**General information**
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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Centre for IT-Intelligent Energy Systems in Cities
Contributors: Ordoudis, C., Pinson, P.
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**Information Uncertainty in Electricity Markets: Introducing Probabilistic Offers**
We propose a shift from the current paradigm of electricity markets treating stochastic producers similarly to conventional ones in terms of their offers. We argue that the producers’ offers should be probabilistic to reflect the limited predictability of renewable energy generation, while we should design market mechanisms to accommodate such offers. We argue that the transition from deterministic offers is a natural next step in electricity markets, by analytically proving our proposal’s equivalence with a two-price conventional market.

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**Integrated Bidding and Operating Strategies for Wind-Storage Systems**

Due to their flexible charging and discharging capabilities, energy storage systems (ESS) are considered a promising complement to wind farms (WFs) participating in electricity markets. This paper presents integrated day-ahead bidding and real-time operation strategies for a wind-storage system to perform arbitrage and to alleviate wind power deviations from day-ahead contracts. The strategy is developed with two-price balancing markets in mind. A mixed integer nonlinear optimization formulation is built to determine optimal offers by taking into account expected wind power forecasting errors and the power balancing capability of the ESS. A modified gradient descent algorithm is designed to solve this nonlinear problem. A number of case studies validate the computational efficiency and optimality of the algorithm. Compared to the existing strategies, the proposed strategies yield increased economic profit, regardless of the temporal dependence of wind power forecasting errors.

**General information**

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Organisations: Department of Applied Mathematics and Computer Science, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets, Tsinghua University  
Contributors: Ding, H., Pinson, P., Hu, Z., Song, Y.  
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Web of Science (2016): Impact factor 4.909  
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DoIs: 10.1109/TSTE.2015.2472576  
Source: FindIt  
Source ID: 276922015  
Research output: Contribution to journal › Journal article – Annual report year: 2016 › Research › peer-review

**Introducing distributed learning approaches in wind power forecasting**

Renewable energy forecasting is now of core interest to both academics, who continuously propose new forecast methodologies, and forecast users for optimal operations and participation in electricity markets. In view of the increasing amount of data being collected at power generation sites, thanks to substantial deployment of generating capacities and increased temporal resolution, it may now be possible to build large models accounting for all space-time dependencies. This will eventually allow to significantly improve the quality of short-term renewable power forecasts. However, in practice, it is often the case that operators of these generation sites do not want to share their data due to competitive interests. Consequently, approaches to privacy-preserving distributed learning are proposed and investigated here. These permit to take advantage of all potential data collected by others, without having to ever share any data, by decomposing the original large learning problem into a number of small learning problems that can be solved in a decentralized manner. As an example, emphasis is placed on Lasso-type estimation of autoregressive models with offsite observations. Different applications on medium to large datasets in Australia (22 wind farms) and France (85 wind farms) are used to illustrate the interest and performance of our proposal.

**General information**

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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets  
Contributors: Pinson, P.  
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Optimal bidding strategy of battery storage in power markets considering performance based regulation and battery cycle life

Large-scale battery storage will become an essential part of the future smart grid. This paper investigates the optimal bidding strategy for battery storage in power markets. Battery storage could increase its profitability by providing fast regulation service under a performance-based regulation mechanism, which better exploits a battery’s fast ramping capability. However, battery life might be decreased by frequent charge–discharge cycling, especially when providing fast regulation service. It is profitable for battery storage to extend its service life by limiting its operational strategy to some degree. Thus, we incorporate a battery cycle life model into a profit maximization model to determine the optimal bids in day-ahead energy, spinning reserve, and regulation markets. Then a decomposed online calculation method to compute cycle life under different operational strategies is proposed to reduce the complexity of the model. This novel bidding model would help investor-owned battery storages better decide their bidding and operational schedules and investors to estimate the battery storage’s economic viability. The validity of the proposed model is proven by case study results.
Optimal coupling of heat and electricity systems: A stochastic hierarchical approach

The large penetration of renewables in the power system increases the need for flexibility. Flexibility gains and wind curtailment reduction can be achieved through a better coordination with other energy systems, in particular with district heating. Loose interactions between these two systems already exist due to the participation of CHPs in both markets. New market structures must be developed in order to exploit these synergies. Recognizing the above-mentioned challenges this paper proposes a stochastic hierarchical formulation of the heat economic dispatch problem in a system with high penetration of CHPs and wind. The objective of this optimization problem is to minimize the heat production cost, subject to constraints describing day-ahead electricity market clearing scenarios. Uncertainties concerning wind power production, electricity demand and rival participants offers are efficiently modelled using a finite set of scenarios. This model takes advantage of existing market structures and provides a decision-making tool for heat system operators. The proposed model is implemented in a case study and results are discussed to show the benefits and applicability of this approach.

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Organisations: Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Contributors: Mitridati, L. M. M., Pinson, P.
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Optimal offering and operating strategies for wind-storage systems with linear decision rules

The participation of wind farm-energy storage systems (WF-ESS) in electricity markets calls for an integrated view of day-ahead offering strategies and real-time operation policies. Such an integrated strategy is proposed here by co-optimizing offering at the day-ahead stage and operation policy to be used at the balancing stage. Linear decision rules are seen as a natural approach to model and optimize the real-time operation policy. These allow enhancing profits from balancing markets based on updated information on prices and wind power generation. Our integrated strategies for WF-ESS in electricity markets are optimized under uncertainty in both wind power and price predictions. The resulting stochastic optimization problem readily yields optimal offers and linear decision rules. By adding a risk-aversion term in form of conditional value at risk into the objective function, the optimization model additionally provides flexibility in finding a trade-off between profit maximization and risk management. Uncertainty in wind power generation, as well as day-ahead and balancing prices, takes the form of scenario sets, permitting to reformulate the optimization problem as a linear program. Case studies validate the effectiveness of the strategy proposed by highlighting and quantifying benefits w.r.t. other existing strategies.

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Optimal offering and operating strategies for wind-storage systems with linear decision rules

The participation of wind farm-energy storage systems (WF-ESS) in electricity markets calls for an integrated view of day-ahead offering strategies and real-time operation policies. Such an integrated strategy is proposed here by co-optimizing offering at the day-ahead stage and operation policy to be used at the balancing stage. Linear decision rules are seen as a natural approach to model and optimize the real-time operation policy. These allow enhancing profits from balancing markets based on updated information on prices and wind power generation. Our integrated strategies for WF-ESS in electricity markets are optimized under uncertainty in both wind power and price predictions. The resulting stochastic optimization problem readily yields optimal offers and linear decision rules. By adding a risk-aversion term in form of conditional value at risk into the objective function, the optimization model additionally provides flexibility in finding a trade-off between profit maximization and risk management. Uncertainty in wind power generation, as well as day-ahead and balancing prices, takes the form of scenario sets, permitting to reformulate the optimization problem as a linear program. Case studies validate the effectiveness of the strategy proposed by highlighting and quantifying benefits w.r.t. other existing strategies.

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Optimal Offering Strategies for Wind Power in Energy and Primary Reserve Markets

Wind power generation is to play an important role in supplying electric power demand, and will certainly impact the design of future energy and reserve markets. Operators of wind power plants will consequently develop adequate offering strategies, accounting for the market rules and the operational capabilities of the turbines, e.g., to participate in primary reserve markets. We consider two different offering strategies for joint participation of wind power in energy and primary reserve markets, based on the idea of proportional and constant splitting of potentially available power generation from the turbines. These offering strategies aim at maximizing expected revenues from both market floors using probabilistic forecasts for wind power generation, complemented with estimated regulation costs and penalties for failing to provide primary reserve. A set of numerical examples, as well as a case-study based on real-world data, allows illustrating and discussing the properties of these offering strategies. An important conclusion is that, even though technically possible, it may not always make sense for wind power to aim at providing system services in a market environment.

General information

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Population Dynamics for Renewables in Electricity Markets: A Minority Game View

The dominance of fluctuating and intermittent stochastic renewable energy sources (RES) has introduced uncertainty in power systems which in turn, has challenged how electricity market operate. In this context, there has been significant research in developing strategies for RES producers, which however typically focuses on the decision process of a single producer, assuming unrealistic access to aspects of information about the power system. This paper analyzes the behavior of an entire population of stochastic producers in an electricity market using as basis a minority game: the El Farol Bar problem. We illustrate how uncomplicated strategies based on a adaptive learning rules lead to the coordination among RES producers and a Pareto efficient outcome.

Probabilistic energy forecasting: Global Energy Forecasting Competition 2014 and beyond

The energy industry has been going through a significant modernization process over the last decade. Its infrastructure is being upgraded rapidly. The supply, demand and prices are becoming more volatile and less predictable than ever before. Even its business model is being challenged fundamentally. In this competitive and dynamic environment, many decision-making processes rely on probabilistic forecasts to quantify the uncertain future. Although most of the papers in the energy forecasting literature focus on point or singlevalued forecasts, the research interest in probabilistic energy forecasting research has taken off rapidly in recent years. In this paper, we summarize the recent research progress on probabilistic energy forecasting. A major portion of the paper is devoted to introducing the Global Energy Forecasting Competition 2014 (GEFCom2014), a probabilistic energy forecasting competition with four tracks on load, price, wind and solar forecasting, which attracted 581 participants from 61 countries. We conclude the paper with 12 predictions for the next decade of energy forecasting.
Ranking Method for Peak-Load Shifting Considering Different Types of Data

Management measures for peak-load shifting are employed to alleviate power shortages during the peak hours in some countries with power-supply shortages, such as China. One of the most popular measures is to rank the electricity users with respect to their relative importance in the society. In ranking the sequence, the decision maker may encounter difficulties because the types of data employed for this purpose are not consistent. Thus, a ranking method capable of handling different types of data is necessary and presented in this paper. To prioritize electricity users in a reasonable manner, an evaluation system for the purpose of peak-load shifting is established from three aspects: economic, social, and environmental impacts. Then a mixed-data dominance method is employed in this work to determine the comprehensive closeness degree of each user under each index, and an optimal comprehensive weight model is then presented with both the subjective weights and objective weights. Based on the attained optimal comprehensive weight and the comprehensive closeness degree, the weighted closeness degree of each electricity user can be calculated and the final ranking result for all electricity users obtained. The proposed approach is demonstrated by actual data of Guangzhou city in China.
RESGen: Renewable Energy Scenario Generation Platform
Space-time scenarios of renewable power generation are increasingly used as input to decision-making in operational problems. They may also be used in planning studies to account for the inherent uncertainty in operations. Similarly using scenarios to derive chance-constraints or robust optimization sets for corresponding optimization problems is useful in a power system context. Generating and evaluating such space-time scenarios is difficult. While quite a number of proposals have appeared in the literature, a gap between methodological proposals and actual usage in operational and planning studies remains. Consequently, our aim here is to propose an open-source platform for space-time probabilistic forecasting of renewable energy generation (wind and solar power). This document covers both methodological and implementation aspects, to be seen as a companion document for the open-source scenario generation platform. It can generate predictive densities, trajectories and space-time interdependencies for renewable energy generation. The underlying model works as a post-processing of point forecasts. For illustration, two setups are considered: the case of day-ahead forecasts to be issued once a day, and for rolling windows with regular updates, with application to the western part of the United States, with both wind and solar power generation.
process may cope with serious operational challenges such as severe power shortage in real-time due to erroneous wind power forecasts in day-ahead market. To overcome such situations, several solutions can be considered such as adding flexible resources to the system. In this paper, we address another potential solution based on information sharing in which market players share their own wind power forecasts with others in day-ahead market. This solution may improve the functioning of sequential market-clearing process through making more informed day-ahead schedules, which reduces the need for balancing resources in real-time operation. This paper numerically evaluates the potential value of sharing forecasts for the whole system in terms of system cost reduction. Besides, its impact on each market player’s profit is analyzed. The framework of this study is based on a stochastic two-stage market setup and complementarity modeling, which allows us to gain further insights into information sharing impacts.

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Stochastic Integrated Market for Electric Power and Natural Gas Systems

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Strategic wind power trading considering rival wind power production

In an electricity market with high share of wind power, it is expected that wind power producers may exercise market power. However, wind producers have to cope with wind’s uncertain nature in order to optimally offer their generation, whereas in a market with more than one wind producers, uncertainty of rival wind power generation should also be considered. Under this context, this paper addresses the impact of rival wind producers on the offering strategy and profits of a pricemaker wind producer. A stochastic day-ahead market setup is considered, which optimizes the day-ahead schedules considering a number of foreseen real-time scenarios. The results indicate that strategic wind producer is more likely to exercise market power having a mid-mean or low-mean forecast distribution, rather than having a high-mean one. Furthermore, it is observed that its offering strategy varies considerably depending on the rival’s wind generation, given that its own expected generation is not high. Finally, as anticipated, expected system cost is higher when both wind power
producers are expected to have low wind power generation

Trading Strategies for Distribution Company with Stochastic Distributed Energy Resources.
This paper proposes a methodology to address the trading strategies of a proactive distribution company (PDISCO) engaged in the transmission-level (TL) markets. A one-leader multi-follower bilevel model is presented to formulate the gaming framework between the PDISCO and markets. The lower-level (LL) problems include the TL day-ahead market and scenario-based real-time markets, respectively with the objectives of maximizing social welfare and minimizing operation cost. The upper-level (UL) problem is to maximize the PDISCO's prot across these markets. The PDISCO's strategic oers/bids interactively in uence the outcomes of each market. Since the LL problems are linear and convex, while the UL problem is non-linear and non-convex, an equivalent primal-dual approach is used to reformulate this bilevel model to a solvable mathematical program with equilibrium constraints (MPEC). The effectiveness of the proposed model is verified by case studies.

Due to the inherent uncertainty involved in renewable energy forecasting, uncertainty quantification is a key input to maintain acceptable levels of reliability and profitability in power system operation. A proposal is formulated and evaluated here for the case of solar power generation, when only power and meteorological measurements are available, without skyimaging and information about cloud passages. Our empirical investigation reveals that the distribution of forecast errors do not follow any of the common parametric densities. This therefore motivates the proposal of a nonparametric approach to generate very short-term predictive densities, i.e., for lead times between a few minutes to one hour ahead, with fast frequency updates. We rely on an Extreme Learning Machine (ELM) as a fast regression model, trained in varied ways to obtain both point and quantile forecasts of solar power generation. Four probabilistic methods are implemented as benchmarks. Rival approaches are evaluated based on a number of test cases for two solar power generation sites in different climatic regions, allowing us to show that our approach results in generation of skilful and reliable probabilistic forecasts in a computationally efficient manner.

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Very-short-term wind power probabilistic forecasts by sparse vector autoregression.
A spatio-temporal method for producing very-short-term parametric probabilistic wind power forecasts at a large number of locations is presented. Smart grids containing tens, or hundreds, of wind generators require skilled very-short-term forecasts to operate effectively, and spatial information is highly desirable. In addition, probabilistic forecasts are widely regarded as necessary for optimal power system management as they quantify the uncertainty associated with point forecasts. Here we work within a parametric framework based on the logit-normal distribution and forecast its parameters. The location parameter for multiple wind farms is modelled as a vector-valued spatiotemporal process, and the scale parameter is tracked by modified exponential smoothing. A state-of-the-art technique for fitting sparse vector autoregressive models is employed to model the location parameter and demonstrates numerical advantages over conventional vector autoregressive models. The proposed method is tested on a dataset of 5 minute mean wind power generation at 22 wind farms in Australia. 5-minute-ahead forecasts are produced and evaluated in terms of point and probabilistic forecast skill scores and calibration. Conventional autoregressive and vector autoregressive models serve as benchmarks.

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Wind offering in energy and reserve markets

The increasing penetration of wind generation in power systems to fulfil the ambitious European targets will make wind power producers to play an even more important role in the future power system. Wind power producers are being incentivized to participate in reserve markets to increase their revenue, since currently wind turbine/farm technologies allow them to provide ancillary services. Thus, wind power producers are to develop offering strategies for participation in both energy and reserve markets, accounting for market rules, while ensuring optimal revenue. We consider a proportional offering strategy to optimally decide upon participation in both markets by maximizing expected revenue from day-ahead decisions while accounting for estimated regulation costs for failing to provide the services. An evaluation of considering the same proportional splitting of energy and reserve in both day-ahead and balancing market is performed. A set of numerical examples illustrate the behavior of such strategy. An important conclusion is that the optimal split of the available wind power between energy and reserve strongly depends upon prices and penalties on both market trading floors.

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Wind power forecasting: IEA Wind Task 36 & future research issues

This paper presents the new International Energy Agency Wind Task 36 on Forecasting, and invites to collaborate within the group. Wind power forecasts have been used operatively for over 20 years. Despite this fact, there are still several possibilities to improve the forecasts, both from the weather prediction side and from the usage of the forecasts. The new International Energy Agency (IEA) Task on Forecasting for Wind Energy tries to organise international collaboration,
among national meteorological centres with an interest and/or large projects on wind forecast improvements (NOAA, DWD, MetOffice, met.no, DMI,...), operational forecaster and forecast users. The Task is divided in three work packages: Firstly, a collaboration on the improvement of the scientific basis for the wind predictions themselves. This includes numerical weather prediction model physics, but also widely distributed information on accessible datasets. Secondly, we will be aiming at an international pre-standard (an IEA Recommended Practice) on benchmarking and comparing wind power forecasts, including probabilistic forecasts. This WP will also organise benchmarks, in cooperation with the IEA Task WakeBench. Thirdly, we will be engaging end users aiming at dissemination of the best practice in the usage of wind power predictions. As first results, an overview of current issues for research in short-term forecasting of wind power is presented.

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Analysis of Strategic Wind Power Participation in Energy Market using MASCEM simulator
In recent years the reassessment of remuneration schemes for renewable sources in several European countries has motivated the increase of wind power generation participation in electricity markets. Moreover, the continuous growth of wind power generation, as well as the evolution of wind turbines technology, suggests that wind power plants may participate in both energy and ancillary services markets with strategic behavior to improve their benefits. Thus, wind power generation with strategic behavior may have impact on market equilibrium and pricing. This paper evaluates the impact of a proportional offering strategy for wind power plants to participate in both energy and ancillary services markets. MASCEM (Multi-Agent System for Competitive Electricity Markets) is used to simulate and validate the impact of wind power plants in market equilibrium. A case study based on real and recent data for the Iberian market and its specific rules is simulated in MASCEM.

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Contributors: Soares, T., Santos, G., Pinto, T., Morais, H., Pinson, P., Vale, Z.
An Integrated Multiperiod OPF Model with Demand Response and Renewable Generation Uncertainty

Renewable energy sources such as wind and solar have received much attention in recent years, and large amount of renewable generation is being integrated to the electricity networks. A fundamental challenge in a power system operation is to handle the intermittent nature of the renewable generation. In this paper we present a stochastic programming approach to solve a multiperiod optimal power flow problem under renewable generation uncertainty. The proposed approach consists of two stages. In the first stage, operating points for the conventional power plants are determined. The second stage realizes generation from the renewable resources and optimally accommodates it by relying on the demand-side flexibilities and limited available flexibilities from the conventional generating units. The proposed model is illustrated on a 4-bus and a 39-bus system. Numerical results show that with small flexibility on the demand-side substantial benefits in terms of re-dispatch costs can be achieved. The proposed approach is tested on all standard IEEE test cases up to 300 buses for a wide variety of scenarios.

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.
Economic Dispatch of Demand Response Balancing through Asymmetric Block Offers

This paper proposes a method of describing the load shifting ability of flexible electrical loads in a manner suitable for existing power system dispatch frameworks. The concept of an asymmetric block offer for flexible loads is introduced. This offer structure describes the ability of a flexible load to provide a response to the power system and the subsequent need to recover. The conventional system dispatch algorithm is altered to facilitate the dispatch of demand response units alongside generating units using the proposed offer structure. The value of demand response is assessed through case studies that dispatch flexible supermarket refrigeration loads for the provision of regulating power. The demand resource is described by a set of asymmetric blocks, and a set of four blocks offers is shown to offer cost savings for the procurement of regulating power in excess of 20%. For comparative purposes, the cost savings achievable with a fully observable and controllable demand response resource are evaluated, using a time series model of the refrigeration loads. The fully modeled resource offers greater savings; however, the difference is small and potentially insufficient to justify the investment required to fully model and control individual flexible loads.
Forecasting for dynamic line rating

This paper presents an overview of the state of the art on the research on Dynamic Line Rating forecasting. It is directed at researchers and decision-makers in the renewable energy and smart grids domain, and in particular at members of both the power system and meteorological community. Its aim is to explain the details of one aspect of the complex interconnection between the environment and power systems. The ampacity of a conductor is defined as the maximum constant current which will meet the design, security and safety criteria of a particular line on which the conductor is used. Dynamic Line Rating (DLR) is a technology used to dynamically increase the ampacity of electric overhead transmission lines. It is based on the observation that the ampacity of an overhead line is determined by its ability to dissipate into the environment the heat produced by Joule effect. This in turn is dependent on environmental conditions such as the value of ambient temperature, solar radiation, and wind speed and direction. Currently, conservative static seasonal estimations of meteorological values are used to determine ampacity. In a DLR framework, the ampacity is estimated in real time or quasi-real time using sensors on the line that measure conductor temperature, tension, sag or environmental parameters such as wind speed and air temperature. Because of the conservative assumptions used to calculate static seasonal ampacity limits and the variability of weather parameters, DLRs are considerably higher than static seasonal ratings. The latent transmission capacity made available by DLRs means the operation time of equipment can be extended, especially in the current power system scenario, where power injections from Intermittent Renewable Sources (IRS) put stress on the existing infrastructure. DLR can represent a solution for accommodating higher renewable production whilst minimizing or postponing network reinforcements. On the other hand, the variability of DLR with respect to static seasonal ratings makes it particularly difficult to exploit, which explains the slow take-up rate of this technology. In order to facilitate the integration of DLR into power system operations, research has been launched into DLR forecasting, following a similar avenue to IRS production forecasting, i.e. based on a mix of statistical methods and meteorological forecasts. The development of reliable DLR forecasts will no doubt be seen as a necessary step for integrating DLR into power system management and reaping the expected benefits.
Foreword for the special section on wind and solar energy: uncovering and accommodating their impacts on electricity markets

From responsibility to accountability: Electricity market mechanisms accommodating probabilistic offers
Generation of scenarios from calibrated ensemble forecasts with a dynamic ensemble copula coupling approach

Probabilistic forecasts in the form of ensemble of scenarios are required for complex decision making processes. Ensemble forecasting systems provide such products but the spatio-temporal structures of the forecast uncertainty is lost when statistical calibration of the ensemble forecasts is applied for each lead time and location independently. Non-parametric approaches allow the reconstruction of spatio-temporal joint probability distributions at a low computational cost. For example, the ensemble copula coupling (ECC) method consists in rebuilding the multivariate aspect of the forecast from the original ensemble forecasts. Based on the assumption of error stationarity, parametric methods aim to fully describe the forecast dependence structures. In this study, the concept of ECC is combined with past data statistics in order to account for the autocorrelation of the forecast error. The new approach which preserves the dynamical development of the ensemble members is called dynamic ensemble copula coupling (d-ECC). The ensemble based empirical copulas, ECC and d-ECC, are applied to wind forecasts from the high resolution ensemble system COSMO-DEEPS run operationally at the German weather service. The generated scenarios are assessed in the form of time series by means of multivariate verification tools and in a product oriented framework. Verification results over a 3 month period show that the innovative method d-ECC outperforms or performs as well as ECC in all investigated aspects. In particular, the temporal variability of the time trajectories are better captured with d-ECC which preserves the information content of the original scenarios.

Improving offering strategies for wind farms enhanced with storage capability

Due to the flexible charging and discharging capability, energy storage system (ESS) is thought of as a promising complement to wind farms (WF) in participating into electricity markets. This paper proposes a reserve-based real-time operation strategy of ESS to make arbitrage and to alleviate the wind power deviation from day-ahead contracts. Taking into account the operation strategy as well as two-price balancing market rules, a day-ahead bidding strategy of WF-ESS system is put forward and formulated. A modified gradient descent algorithm is described to solve the formulations. In the case studies, the computational efficiency of the algorithm is validated firstly. Moreover, a number of scenarios with/without considering the temporal dependence of wind power forecast error are designed and employed to compare the proposed strategy with other common ones in terms of profit.
Methodology and forecast products for the optimal offering of ancillary services from wind in a market environment

In this report models for extreme negative wind power forecast errors are presented. The models can be applied to estimate levels below which the wind power rarely drops. Such levels could be called “certain-levels” or “guaranteed levels” of wind power, well knowing that full guarantee never can be given. The estimated levels are obtained by modelling the error from already existing wind power forecasting software, this is accomplished by modelling the residuals with statistical extreme value techniques.

The forecasts can be used in the operation of power systems with significant amounts of wind power for example in the planning of ancillary power services, where the level of available wind power with a high degree of certainty is important to know.

The presented extreme value models are applied to negative forecast residuals from state-of-the-art wind power forecast software. This enables the estimation of return levels below which the extreme wind power forecast error events occur only at a specified rate, e.g. once a month or once every year. The techniques allows extrapolation beyond the available data period. In the study data from 1.5 years is used. It consists of hourly wind power production in the two regions of Denmark (DK1 and DK2) and corresponding wind power forecasts. The wind power forecasts are generated using the software WPPT and are based on the outcome of three numerical weather prediction models. They cover horizons from 1 to 42 hours ahead in time and are updated each hour.

In the report a range of extreme value models are suggested. They are of increasing complexity and a model selection is carried using statistical measures and test. A normal procedure when building forecasting models is to divide the data into a learning and a test set to cross-validate the results in order to avoid over-fitting the models. This is hardly ever possible for extreme value analysis, instead the model selection and evaluation sole rely on statistical techniques such as correlation measures, likelihood ratio-tests and information about uncertainty, for example in the form of confidence bands on parameter estimates and predictions.

The foundation to statistical extreme value theory was set by Fisher and Tippett in 1928 and later developed by Gumbel (1958). Since then it has been used for modelling extremes in a wide range of applications. Typical applications are for estimation of extreme weather induced phenomena, for example extreme water levels in a river, wind levels or at sea for design of dykes (de Haan and de Ronde, 1998). In insurance and finance the extreme value modelling is widespread (Embrechts et al., 1997). Extreme value statistics for energy and power applications is also widely used, for example for planning in wind power operation (Horvat et al., 2013) and peak wind prediction (Cook, 1982) and (Friederichs and Thorarinsdottir, 2012). Several books provide comprehensive introductions to extreme value theory, for example Coles (2001) and Beirlant et al. (2006). A really good overview of available extreme value analysis software is given by Stephenson and Gilleland, 2005. In the present study the R R Core Team (2013) package extRemes Gilleland and Katz (2011) is used.
On Quantification of Flexibility in Power Systems

Large scale integration of fluctuating and nondispatchable generation and variable transmission patterns induce high uncertainty in power system operation. In turn, transmission system operators (TSOs) need explicit information about available flexibility to maintain a desired reliability level at a reasonable cost. In this paper, locational flexibility is defined and a unified framework to compare it against forecast uncertainty is introduced. Both metrics are expressed in terms of ramping rate, power and energy and consider the network constraints. This framework is integrated into the operational practice of the TSO using a robust reserve procurement strategy which guarantees optimal system response in the worst-case realization of the uncertainty. An illustrative three-node system is used to investigate the procurement method. Finally, the locational flexibility for a larger test system is presented.

Optimal dynamic capacity allocation of HVDC interconnections for cross-border exchange of balancing services in presence of uncertainty.

The deployment of large shares of stochastic renewable energy, e.g., wind power, may bring important economic and environmental benefits to the power system. Nonetheless, their efficient integration depends on the ability of the power system to cope with their inherent variability and the uncertainty arising from their partial predictability. Considering that the existing setup of the European electricity markets promotes the spatial coordination of neighbouring power systems only on the day-ahead market stage, regional system operators have to rely mainly on their internal balancing resources in order to guarantee system security. However, as power systems are forced to operate closer to their technical limits, where flexible generation resources become scarce, the conventional market paradigm may not be able to respond effectively on the wide range of uncertainty. The operational flexibility of the power system depends both on the technical parameters of its components, i.e., generators and transmission infrastructure, as well as on the operational practices that make optimal use of the available assets. This work focuses on alternative market designs that enable sharing of cross-border balancing resources between adjacent power systems through High Voltage Direct Current (HVDC) interconnections which provide increased controllability. In this context, we formulate a stochastic market-clearing algorithm that attains full spatio-temporal integration of reserve capacity, day-ahead and balancing markets. Against this benchmark we compare two deterministic market designs with varying degrees of coordination between the reserve capacity and energy services, both followed by a real-time mechanism. Our study reveals the inefficiency of deterministic approaches as the shares of wind power increase. Nevertheless, enforcing a tighter coordination between the reserves and energy trading floors may improve considerably the expected system cost compared to a sequential market design. Aiming to provide some insights for improvement of the sequential market-clearing, we analyse the effect of explicit transmission allocation between energy and reserves for different HVDC capacities and identify the market dynamics that dictate the optimal ratio.
Price-Maker Wind Power Producer Participating in a Joint Day-Ahead and Real-Time Market

The large scale integration of stochastic renewable energy introduces significant challenges for power system operators and disputes the efficiency of the current market design. Recent research embeds the uncertain nature of renewable sources by modelling electricity markets as a two-stage stochastic problem, co-optimizing day-ahead and real-time dispatch. In this framework, we introduce a bilevel model to derive the optimal bid of a strategic wind power producer acting as price-maker both in day-ahead and real-time stages. The proposed model is a Mathematical Program with Equilibrium Constraints (MPEC) that is reformulated as a single-level Mixed-Integer Linear Program (MILP), which can be readily solved. Our analysis shows that adopting strategic behaviour may improve producer’s expected profit as the share of wind power increases. However, this incentive diminishes in power systems where available flexible capacity is high enough to ensure an efficient market operation.

Probabilistic maximum-value wind prediction for offshore environments

High wind speeds can pose a great risk to structures and operations conducted in offshore environments. When forecasting wind speeds, most models focus on the average wind speeds over a given period, but this value alone
represents only a small part of the true wind conditions. We present statistical models to predict the full distribution of the maximum-value wind speeds in a 3h interval. We take a detailed look at the performance of linear models, generalized additive models and multivariate adaptive regression splines models using meteorological covariates such as gust speed, wind speed, convective available potential energy, Charnock, mean sea-level pressure and temperature, as given by the European Center for Medium-Range Weather Forecasts forecasts. The models are trained to predict the mean value of maximum wind speed, and the residuals from training the models are used to develop the full probabilistic distribution of maximum wind speed. Knowledge of the maximum wind speed for an offshore location within a given period can inform decision-making regarding turbine operations, planned maintenance operations and power grid scheduling in order to improve safety and reliability, and probabilistic forecasts result in greater value to the end-user. The models outperform traditional baseline forecast methods and achieve low predictive errors on the order of 1–2 m s⁻¹. We show the results of their predictive accuracy for different lead times and different training methodologies.

Quantile forecast discrimination ability and value

While probabilistic forecast verification for categorical forecasts is well established, some of the existing concepts and methods have not found their equivalent for the case of continuous variables. New tools dedicated to the assessment of forecast discrimination ability and forecast value are introduced here, based on quantile forecasts being the base product for the continuous case. The relative user characteristic (RUC) curve and the quantile value plot allow analysing the performance of a forecast for a specific user in a decision-making framework. The RUC curve is designed as a user-based discrimination tool and the quantile value plot translates forecast discrimination ability in terms of economic value. The relationship between the overall value of a quantile forecast and the respective quantile skill score is also discussed. The application of these new verification approaches and tools is illustrated based on synthetic datasets, as well as for the case of global radiation forecasts from the high resolution ensemble COSMO-DE-EPS of the German Weather Service.
Robust optimisation for self-scheduling and bidding strategies of hybrid CSP-fossil power plants
This paper describes a profit-maximisation model for a hybrid concentrated solar power (CSP) producer participating in a day-ahead market with bilateral contracts, where there is no correlation between the electricity market price and the solar irradiation. Backup system coordination is included between the molten-salt thermal energy storage (TES) and a fossil-fuel backup to overcome solar irradiation insufficiency, but with emission allowances constrained in the backup system to mitigate carbon footprint. A robust optimisation-based approach is proposed to provide the day-ahead self-schedule under the worst-case realisation of uncertainties due to the electricity market prices and the thermal production from the solar field (SF). These uncertainties are modelled by asymmetric prediction intervals around average values. Additionally, a budget parameter is used to parameterise the degree of conservatism of the decision. The decision provides the optimal bidding strategies consisting in supply functions built not only for different budget parameter values, but also for different emission allowance levels. Finally, a realistic case study is presented to show the effectiveness of the proposed approach.

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Stochastic Unit Commitment via Progressive Hedging - Extensive Analysis of Solution Methods
Owing to the massive deployment of renewable power production units over the last couple of decades, the use of stochastic optimization methods to solve the unit commitment problem has gained increasing attention. Solving stochastic unit commitment problems in large-scale power systems requires high computational power, as stochastic models are dramatically more complex than their deterministic counterparts. This paper provides new insight into the potential of Progressive Hedging to decrease the solution time of the stochastic unit commitment problem with a relatively small trade-off in terms of the suboptimality of the solution. Computational studies show that the run-time is at most half of what is
needed to solve the original extensive formulation of the problem, when more than ten wind power scenarios are utilized. These studies demonstrate great potential for solving real-world stochastic unit commitment problems using the Progressive Hedging algorithm.

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The Cobweb Effect in Balancing Markets with Demand Response
Integration of renewable energy sources (RES) like wind into the power system is a high priority in many countries, but it becomes increasingly difficult as renewables reach a significant share of generation. Demand response (DR) can potentially mitigate some of these difficulties, but the best way to control and integrate DR into the power system remains an open question. Integration into existing electricity markets is one option, but dynamic pricing with DR has been observed to be unstable, resulting in oscillations in supply and demand. This so-called Cobweb effect is presented here using the market structure and measurements from the EcoGrid EU demonstration, where five minute electricity pricing is sent to 1900 houses. A new tool for quantifying volatility is presented, and the causes for volatility are investigated. A key outcome of this study shows that increases in social welfare due to DR appear to be limited by the cost of volatility in existing market structures.

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The new IEA Wind Task 36 on Wind Power Forecasting
Wind power forecasts have been used operatively for over 20 years. Despite this fact, there are still several possibilities to improve the forecasts, both from the weather prediction side and from the usage of the forecasts. The new International Energy Agency (IEA) Task on Forecasting for Wind Energy tries to organise international collaboration, among national weather centres with an interest and/or large projects on wind forecast improvements (NOAA, DWD, ...), operational forecaster and forecast users.

The Task is divided in three work packages: Firstly, a collaboration on the improvement of the scientific basis for the wind predictions themselves. This includes numerical weather prediction model physics, but also widely distributed information on accessible datasets. Secondly, we will be aiming at an international pre-standard (an IEA Recommended Practice) on benchmarking and comparing wind power forecasts, including probabilistic forecasts. This WP will also organise benchmarks, in cooperation with the IEA Task WakeBench. Thirdly, we will be engaging end users aiming at dissemination of the best practice in the usage of wind power predictions.
The "Weather Intelligence for Renewable Energies" Benchmarking Exercise on Short-Term Forecasting of Wind and Solar Power Generation.

A benchmarking exercise was organized within the framework of the European Action Weather Intelligence for Renewable Energies ("WIRE") with the purpose of evaluating the performance of state of the art models for short-term renewable energy forecasting. The exercise consisted in forecasting the power output of two wind farms and two photovoltaic power plants, in order to compare the merits of forecasts based on different modeling approaches and input data. It was thus possible to obtain a better knowledge of the state of the art in both wind and solar power forecasting, with an overview and comparison of the principal and the novel approaches that are used today in the field, and to assess the evolution of forecast performance with respect to previous benchmarking exercises. The outcome of this exercise consisted then in proposing new challenges in the renewable power forecasting field and identifying the main areas for improving accuracy in the future.
wind farms employ energy and ancillary service market. Already proposed Proportional Wind Reserve Strategy (PWRS) and a Continuous Wind Reserve Strategy (CWRS) are used to determine the amount of available power for ancillary services. A case study based on real and recent data for Denmark allows evaluating impact on market prices, wind farms' revenue, as well as impact on power system reliability.

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**Automatic Classification of Offshore Wind Regimes With Weather Radar Observations**
Weather radar observations are called to play an important role in offshore wind energy. In particular, they can enable the monitoring of weather conditions in the vicinity of large-scale offshore wind farms and thereby notify the arrival of precipitation systems associated with severe wind fluctuations. The information they provide could then be integrated into an advanced prediction system for improving offshore wind power predictability and controllability. In this paper, we address the automatic classification of offshore wind regimes (i.e., wind fluctuations with specific frequency and amplitude) using reflectivity observations from a single weather radar system. A categorical sequence of most likely wind regimes is estimated from a wind speed time series by combining a Markov-Switching model and a global decoding technique, the Viterbi algorithm. In parallel, attributes of precipitation systems are extracted from weather radar images. These attributes describe the global intensity, spatial continuity and motion of precipitation echoes on the images. Finally, a CART classification tree is used to find the broad relationships between precipitation attributes and wind regimes

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Benefits and challenges of electrical demand response: A critical review

Advances in IT, control and forecasting capabilities have made demand response a viable, and potentially attractive, option to increase power system flexibility. This paper presents a critical review of the literature in the field of demand response, providing an overview of the benefits and challenges of demand response. These benefits include the ability to balance fluctuations in renewable generation and consequently facilitate higher penetrations of renewable resources on the power system, an increase in economic efficiency through the implementation of real-time pricing, and a reduction in generation capacity requirements. Nevertheless, demand response is not without its challenges. The key challenges for demand response centre around establishing reliable control strategies and market frameworks so that the demand response resource can be used optimally. One of the greatest challenges for demand response is the lack of experience, and the consequent need to employ extensive assumptions when modelling and evaluating this resource. This paper concludes with an examination of these assumptions, which range from assuming a fixed linear price–demand relationship for price responsive demand, to modelling the highly diverse, distributed and uncertain demand response resource as a single, centralised negative generator, adopting fixed characteristics and constraints.

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Discussion of "Prediction intervals for short-term wind farm generation forecasts" and "Combined nonparametric prediction intervals for wind power generation"

A new score for the evaluation of interval forecasts, the so-called coverage width-based criterion (CWC), was proposed and utilized. This score has been used for the tuning (in-sample) and genuine evaluation (out-of-sample) of prediction intervals for various applications, e.g., electric load [1], electricity prices [2], general purpose prediction [3], and wind power generation [4], [5]. Indeed, two papers by the same authors appearing in the IEEE Transactions On Sustainable Energy employ that score and use it to conclude on the comparative quality of alternative approaches to interval forecasting of wind power generation.

Early warnings of extreme winds using the ECMWF Extreme Forecast Index

The European FP7 SafeWind Project aims at developing research towards a European vision of wind power forecasting, which requires advanced meteorological support concerning extreme wind events. This study is focused mainly on early warnings of extreme winds in the early medium-range. Three synoptic stations (airports) of North Germany (Bremen, Hamburg and Hannover) were considered for the construction of time series of daily maximum wind speeds. All daily wind extremes were found to be linked to very intense surface cyclonic circulation systems being advected mainly by southwest and northwest flow regimes. Overall, it becomes clear that the first indications of an extreme wind event might come from the ECMWF deterministic and/or probabilistic components capturing very intense weather systems (possible windstorms) in the medium term. For early warnings, all available EPS Extreme Forecast Index (EFI) formulations were used, by linking daily maximum wind speeds to EFI values for different forecast horizons. From all possible EFI schemes deployed for issuing early warnings, the highest skill was found for the Gust Factor formulation (EFI-10FGI). Using EFI-10FGI, the corresponding 99% threshold could provide an early warning for a considerable portion of the > 99% wind extremes, but not for all. By lowering this threshold the number of hits is increased until all extremes are captured (zero misses), although by doing so the number of false alarms increased significantly. Consequently, an optimal trade-off between hits and false alarms has to be made when setting different (critical) EFI thresholds.
Electricity market clearing with improved dispatch of stochastic production

In this paper, we consider an electricity market that consists of a day-ahead and a balancing settlement, and includes a number of stochastic producers. We first introduce two reference procedures for scheduling and pricing energy in the day-ahead market: on the one hand, a conventional network-constrained auction purely based on the least-cost merit order, where stochastic generation enters with its expected production and a low marginal cost; on the other, a counterfactual auction that also accounts for the projected balancing costs using stochastic programming. Although the stochastic clearing procedure attains higher market efficiency in expectation than the conventional day-ahead auction, it suffers from fundamental drawbacks with a view to its practical implementation. In particular, it requires flexible producers (those that make up for the lack or surplus of stochastic generation) to accept losses in some scenarios. Using a bilevel programming framework, we then show that the conventional auction, if combined with a suitable day-ahead dispatch of stochastic producers (generally different from their expected production), can substantially increase market efficiency and emulate the advantageous features of the stochastic optimization ideal, while avoiding its major pitfalls.

A two-node power system serves as both an illustrative example and a proof of concept. Finally, a more realistic case study highlights the main advantages of a smart day-ahead dispatch of stochastic producers.

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Research output: Contribution to journal › Journal article – Annual report year: 2012 › Research › peer-review
Exponential smoothing approaches for prediction in real-time electricity markets

The optimal design of offering strategies for wind power producers is commonly based on unconditional (and, hence, constant) expectation values for prices in real-time markets, directly defining their loss function in a stochastic optimization framework. This is why it may certainly be advantageous to account for the seasonal and dynamic behavior of such prices, hence translating to time-varying loss functions. With that objective in mind, forecasting approaches relying on simple models that accommodate the seasonal and dynamic nature of real-time prices are derived and analyzed. These are all based on the well-known Holt–Winters model with a daily seasonal cycle, either in its conventional form or conditioned upon exogenous variables, such as: (i) day-ahead price; (ii) system load; and (iii) wind power penetration. The superiority of the proposed approach over a number of common benchmarks is subsequently demonstrated through an empirical investigation for the Nord Pool, mimicking practical forecasting for a three-year period over 2008–2011.

FLECH - A Danish market solution for DSO congestion management through DER flexibility services

Future electric power systems will face new operational challenges due to the high penetration of distributed energy resources (DERs). In Denmark distribution system operator (DSO) expects a significant congestion increased in distribution grids. In order to manage these congestions and mobilize the DERs as economically efficient as possible in the future distribution grid, the brand new notion of Flexibility Clearing House (FLECH) is proposed in this paper. With the Aggregator-based offers, the proposed FLECH market has the ability to promote small scale DERs (up to SMW) for actively participating in trading flexibility services, which are stipulated accommodating the various requirements of DSO. Accordingly, the trading setups and processes of the FLECH market are also illustrated in detail. A quantitative example is
Global Energy Forecasting Competition 2012
The Global Energy Forecasting Competition (GEFCom2012) attracted hundreds of participants worldwide, who contributed many novel ideas to the energy forecasting field. This paper introduces both tracks of GEFCom2012, hierarchical load forecasting and wind power forecasting, with details on the aspects of the problem, the data, and a summary of the methods used by selected top entries. We also discuss the lessons learned from this competition from the organizers’ perspective. The complete data set, including the solution data, is published along with this paper, in an effort to establish a benchmark data pool for the community.

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High-quality Wind Power Scenario Forecasts for Decision-making Under Uncertainty in Power Systems
The large scale integration of wind generation in existing power systems requires novel operational strategies and market clearing mechanisms to account for the variable nature of this energy source. An efficient method to cope with this uncertainty is stochastic optimization which however requires high-quality forecasts in the form of scenarios. The main goal of this work is to release a public dataset of wind power forecasts to be used as a reference for future research. To that extent, we provide a complete framework to describe wind power uncertainty in terms of single-valued and probabilistic predictions as well as scenarios representing the spatio-temporal dependence structure of forecast errors. The applicability of the proposed framework is demonstrated with a small-scale stochastic unit commitment model.

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IceWind Inter-comparison of Icing Production Loss Models

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Integrating Renewables in Electricity Markets: Operational Problems

This addition to the ISOR series addresses the analytics of the operations of electric energy systems with increasing penetration of stochastic renewable production facilities, such as wind- and solar-based generation units.

As stochastic renewable production units become ubiquitous throughout electric energy systems, an increasing level of flexible backup provided by non-stochastic units and other system agents is needed if supply security and quality are to be maintained.

Within the context above, this book provides up-to-date analytical tools to address challenging operational problems such as:

- The modeling and forecasting of stochastic renewable power production.
- The characterization of the impact of renewable production on market outcomes.
- The clearing of electricity markets with high penetration of stochastic renewable units.
- The development of mechanisms to counteract the variability and unpredictability of stochastic renewable units so that supply security is not at risk.
- The trading of the electric energy produced by stochastic renewable producers.
- The association of a number of electricity production facilities, stochastic and others, to increase their competitive edge in the electricity market.
- The development of procedures to enable demand response and to facilitate the integration of stochastic renewable units.

This book is written in a modular and tutorial manner and includes many illustrative examples to facilitate its comprehension. It is intended for advanced undergraduate and graduate students in the fields of electric energy systems, applied mathematics and economics. Practitioners in the electric energy sector will benefit as well from the concepts and techniques explained in this book.

Model Identification for Control of Display Units in Supermarket Refrigeration Systems

In this paper we propose a method for identifying and validating a model of the heat dynamics of a supermarket refrigeration display case for the purpose of advanced control. The model is established to facilitate the development of novel model-based control techniques for individual display units in a supermarket refrigeration system. The grey-box modelling approach is adopted, using stochastic differential equations to define the dynamics of the model, combining prior knowledge of the physical system with data-driven modelling. Model identification is performed using the forward
selection method, and the performance of candidate models is evaluated through cross-validation. The model developed in this work uses operational data from a small Danish supermarket. A three-state model is determined to be most appropriate for describing the dynamics of this system. Advanced local control employing the identified model can contribute to the extension of the control capabilities of the entire supermarket refrigeration system.

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Modelling and Assessment of the Capabilities of a Supermarket Refrigeration System for the Provision of Regulating Power
This report presents an analysis of the demand response capabilities of a supermarket refrigeration system, with a particular focus on the suitability of this resource for participation in the regulating power market. An ARMAX model of the system is identified from experimental data, and the model is found to have time constants at 10 and 0.12 hours, indicating the potential for the system to provide flexibility in both the long- and short-term. Direct- and indirect-control architectures are employed to simulate the demand response attainable from the refrigeration system. A number of complexities are revealed that would complicate the task of devising bids on a conventional power market. These complexities are incurred due to the physical characteristics and constraints of the system as well as the particular characteristics of the control frameworks employed. Simulations considering the provision of up- and down-regulation reveal that allowing the system to occupy any state within its feasible region results in a complex behaviour. This would require intensive monitoring and control and would be excessively complicated to communicate to a market operator. By restricting the operating region of the system this behaviour can be simplified. These restrictions result in a loss of optimality, but a result in a resource that can be communicated to the market operator in the form of a bid containing a quantity of power for up- or down-regulation and the duration for which the service can be provided.

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Operational Strategies for Predictive Dispatch of Control Reserves in View of Stochastic Generation
In view of the predictability and stochasticity of wind power generation, transmission system operators (TSOs) can benefit from predictive dispatch of slow and manual control reserves in order to maintain reactive reserve levels for unpredictable events. While scenario-based approaches for stochastic optimization are well suited for this problem, it appears that TSOs
are hesitant in adopting this method into their practice of predictive dispatch. Differences in the formulation of constraints and cost functions, the timing and reserve product constraints influence the dispatch result significantly and yield varying results with different practical implications. To support adoption, there is a need to study relevant parameters and trade-offs to be considered in introducing such methods to operation practice, enabling also the investigation of alternate reserve product constraints, e.g., to enable reserve contribution from storage-constrained units. This paper introduces a framework for comparison of operational strategies for system balancing, proposes criteria for performance assessment and exemplifies a systematic evaluation of several operation strategies.

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**Optimal prediction intervals of wind power generation**
Accurate and reliable wind power forecasting is essential to power system operation. Given significant uncertainties involved in wind generation, probabilistic interval forecasting provides a unique solution to estimate and quantify the potential impacts and risks facing system operation with wind penetration beforehand. This paper proposes a novel hybrid intelligent algorithm approach to directly formulate optimal prediction intervals of wind power generation based on extreme learning machine and particle swarm optimization. Prediction intervals with Associated confidence levels are generated through direct optimization of both the coverage probability and sharpness to ensure the quality. The proposed method does not involve the statistical inference or distribution assumption of forecasting errors needed in most existing methods. Case studies using real wind farm data from Australia have been conducted. Comparing with benchmarks applied, experimental results demonstrate the high efficiency and reliability of the developed approach. It is therefore convinced that the proposed method provides a new generalized framework for probabilistic wind power forecasting with high reliability and flexibility and has a high potential of practical applications in power systems.

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Predictive densities for day-ahead electricity prices using time-adaptive quantile regression

A large part of the decision-making problems actors of the power system are facing on a daily basis requires scenarios for day-ahead electricity market prices. These scenarios are most likely to be generated based on marginal predictive densities for such prices, then enhanced with a temporal dependence structure. A semi-parametric methodology for generating such densities is presented: it includes: (i) a time-adaptive quantile regression model for the 5%-95% quantiles; and (ii) a description of the distribution tails with exponential distributions. The forecasting skill of the proposed model is compared to that of four benchmark approaches and the well-known the generalist autoregressive conditional heteroskedasticity (GARCH) model over a three-year evaluation period. While all benchmarks are outperformed in terms of forecasting skill overall, the superiority of the semi-parametric model over the GARCH model lies in the former's ability to generate reliable quantile estimates.

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Organisations: Department of Applied Mathematics and Computer Science, Department of Electrical Engineering, Center for Electric Power and Energy, Dynamical Systems, ENFOR A/S
Contributors: Jónsson, T., Pinson, P., Madsen, H., Nielsen, H. A.
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Research output: Contribution to journal > Journal article – Annual report year: 2014 > Research > peer-review

Prévoir l’électricité produite par nos énergies renouvelables

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Contributors: Pinson, P.
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Publisher: Nouveau Monde éditions
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Source: PublicationPreSubmission
Source ID: 103385621
Research output: Chapter in Book/Report/Conference proceeding > Book chapter – Annual report year: 2014 > Research > peer-review
Probabilistic forecasting of wind power generation using extreme learning machine.

Accurate and reliable forecast of wind power is essential to power system operation and control. However, due to the nonstationarity of wind power series, traditional point forecasting can hardly be accurate, leading to increased uncertainties and risks for system operation. This paper proposes an extreme learning machine (ELM)-based probabilistic forecasting method for wind power generation. To account for the uncertainties in the forecasting results, several bootstrap methods have been compared for modeling the regression uncertainty, based on which the pairs bootstrap method is identified with the best performance. Consequently, a new method for prediction intervals formulation based on the ELM and the pairs bootstrap is developed. Wind power forecasting has been conducted in different seasons using the proposed approach with the historical wind power time series as the inputs alone. The results demonstrate that the proposed method is effective for probabilistic forecasting of wind power generation with a high potential for practical applications in power systems.

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Scopus rating (2014): CiteScore 5.31 SJR 2.475 SNIP 3.461
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Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review

Probabilistic forecasts of wind power generation accounting for geographically dispersed information
Forecasts of wind power generation in their probabilistic form are a necessary input to decision-making problems for reliable and economic power systems operations in a smart grid context. Thanks to the wealth of spatially distributed data, also of high temporal resolution, such forecasts may be optimized by accounting for spatio-temporal effects that are so far merely considered. The way these effects may be included in relevant models is described for the case of both parametric and nonparametric approaches to generating probabilistic forecasts. The resulting predictions are evaluated on the real-world test case of a large offshore wind farm in Denmark (Nysted, 165 MW), where a portfolio of 19 other wind farms is seen as a set of geographically distributed sensors, for lead times between 15 minutes and 8 hours. Forecast improvements are shown to mainly come from the spatio-temporal correction of the first order moments of predictive densities. The best performing approach, based on adaptive quantile regression, using spatially corrected point forecasts as input, consistently outperforms the state-of-the-art benchmark based on local information only, by 1.5%-4.6%, depending upon the lead time.

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Contributors: Tastu, J., Pinson, P., Trombe, P., Madsen, H.
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Redefining the merit order of stochastic generation in forward markets.
This letter proposes a new merit order for the dispatch of stochastic production in forward markets (e.g., dayahead markets). The proposed merit order considers not only the marginal cost of the stochastic generating unit, which is often very low or zero, but also the projected cost of balancing its energy deviations during the real-time operation of the power system. We show, through an illustrative example, that the proposed merit order leads to increased market efficiency as the penetration of stochastic generation in the electricity market grows.

Regulating Power from Supermarket Refrigeration
This paper presents an analysis of the demand response capabilities of a supermarket refrigeration system, with a particular focus on the suitability for participation in the regulating power market. An ARMAX model of a supermarket refrigeration system is identified using experimental data from the Danfoss refrigeration test centre. The complexities of modelling demand response are demonstrated through simulation. Simulations are conducted by placing the identified model in a direct-control demand response architecture, with power reference tracking using model predictive control. The energy-limited nature of demand response from refrigeration is identified as the key consideration when considering participation in the regulating power market. It is demonstrated that by restricting the operating regions of the supermarket refrigeration system, a simple relationship can be found between the available up- or down-regulation power, and the
Renewables in Electricity Markets

Electricity is nowadays commonly exchanged through electricity markets, designed in a context where dispatchable generators, with non-negligible marginal costs, were dominating. By depending primarily on conventional (fossil, hydro and nuclear) power generation based on marginal pricing, deterministic market designs were considered adequate with straightforward setups consisting of a forward optimal allocation accompanied by a real-time balancing mechanism. However, as the share of renewable sources of energy (RES) increases, such market designs tend to become inefficient since they were not designed to take into account the uncertainty brought by the substantial variability and limited predictability associated with stochastic sources, most notably wind power and solar energy. Due to these developments, the need for decision making models able to account for the uncertainty introduced by high shares of renewable sources and for new market designs has emerged. Consequently, the research vision of our research group focuses on the large scale integration of RES in the power system under a liberalized market environment by providing a set of methods and tools for forecasting power generation from renewables, and on the adaption of electricity market designs and power system operations to the aforementioned characteristics of renewables. Additionally, the aim of the research group is supplemented by providing the appropriate frameworks for secure future investments in the field of renewables being in line with the worldwide environmental concern to reduce carbon emissions and for the economic energy system integration. In this context, the central objective of the group is to deal with the uncertainty in energy systems and to rethink electricity markets design by taking uncertainty into consideration. This is accomplished by bridging the gap between relevant expertise in power systems, data mining and optimization, meteorology, as well as energy economics. As the name of the group suggests, the specific areas of research of its members are divided in two groups: i) Energy Analytics and ii) Markets. In Energy Analytics we focus on forecasting the various quantities of energy systems, such as wind power, energy consumption and the corresponding prices, and on developing decision making tools in a market environment. This is supported by a serious commitment in data mining and analysis of increasing quantity of power and meteorological data with high spatial and temporal resolutions. While research on Markets considers the development of new systems and market models that will be able to accommodate high shares of RES. These designs are tested under various uncertainties both from the generation and the demand side. The aim is to propose various approaches to market settlements (i.e. joint spot and balancing markets), define new market products and accomplish the efficient coordination of market and system operators. Furthermore, we follow closely the recent trends in EU which involve coupled day-ahead markets for the member states and co-ordination for balancing, by looking into coupling mechanisms that promote the effective cooperation between the power systems of various countries.
Towards electricity markets accommodating uncertain offers
The use of renewable energy sources of energy and in particular wind and solar has been on the rise over the last decades with plans to increase it even more. Such developments introduce significant challenges in existing power systems and can result in high electricity prices and costly infrastructure investments. In this paper we propose a new electricity market mechanism whereby the uncertain and dynamic nature of wind power and other stochastic sources is embedded in the market mechanism itself, by modelling producers' bids as probabilistic estimates. An extension on the bilevel programming formulation of an electricity market, based on the Continuous Ranked Probability Score (CRPS) reduces the impact of poor estimates for both the stochastic producers and the system operator. We introduce a simulation setting which first demonstrates that impact and then proceed to illustrate the main features our market setup and compare it with a conventional electricity market and a standard bilevel setup.

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Weather radars – the new eyes for offshore wind farms?
Offshore wind fluctuations are such that dedicated prediction and control systems are needed for optimizing the management of wind farms in real-time. In this paper, we present a pioneer experiment – Radar@Sea – in which weather radars are used for monitoring the weather at the Horns Rev offshore wind farm, in the North Sea. First, they enable the collection of meteorological observations at high spatio-temporal resolutions for enhancing the understanding of meteorological phenomena that drive wind fluctuations. And second, with the extended visibility they offer, they can provide relevant inputs to prediction systems for anticipating changes in the wind fluctuation dynamics, generating improved wind power forecasts and developing specific control strategies. However, integrating weather radar observations into automated decision support systems is not a plug-and-play task, and it is important to develop a multi-disciplinary approach linking meteorology and statistics. Here, (i) we describe the settings of the Radar@Sea experiment, (ii) we report the experience gained with these new remote sensing tools, (iii) we illustrate their capabilities with some concrete meteorological events observed at Horns Rev and (iv) we discuss the future perspectives for weather radars in wind energy. Copyright © 2013 John Wiley & Sons, Ltd.

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Wind resource assessment and wind power forecasting

General information
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Editors: Hvidtfeldt Larsen, H., Sønderberg Petersen, L.
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DTU_INTL_ENERGY_REP_2014_WIND_72_78.pdf
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A bilevel model for electricity retailers' participation in a demand response market environment

Demand response programmes are seen as one of the contributing solutions to the challenges posed to power systems by the large-scale integration of renewable power sources, mostly due to their intermittent and stochastic nature. Among demand response programmes, real-time pricing schemes for small consumers are believed to have significant potential for peak-shaving and load-shifting, thus relieving the power system while reducing costs and risk for energy retailers. This paper proposes a game theoretical model accounting for the Stackelberg relationship between retailers (leaders) and consumers (followers) in a dynamic price environment. Both players in the game solve an economic optimisation problem subject to stochasticity in prices, weather-related variables and must-serve load. The model allows the determination of the dynamic price-signal delivering maximum retailer profit, and the optimal load pattern for consumers under this pricing. The bilevel programme is reformulated as a single-level MILP, which can be solved using commercial off-the-shelf optimisation software. In an illustrative example, we simulate and compare the dynamic pricing scheme with fixed and time-of-use pricing. We find that the dynamic pricing scheme is the most effective in achieving load-shifting, thus reducing retailer costs for energy procurement and regulation in the wholesale market. Additionally, the redistribution of the saved costs between retailers and consumers is investigated, showing that real-time pricing is less convenient than fixed and time-of-use price for consumers. This implies that careful design of the retail market is needed. Finally, we carry out a sensitivity analysis to analyse the effect of different levels of consumer flexibility.

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Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems
Contributors: Zugno, M., Morales González, J. M., Pinson, P., Madsen, H.
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Journal: Energy Economics
A comparison between the ECMWF and COSMO Ensemble Prediction Systems applied to short-term wind power forecasting on real data

Wind power forecasting (WPF) represents a crucial tool to reduce problems of grid integration and to facilitate energy trading. By now it is advantageous to associate a deterministic forecast with a probabilistic one, in order to give to the end-users information about prediction uncertainty together with a single forecast power value for each future time horizon. A comparison between two different ensemble forecasting models, ECMWF EPS (Ensemble Prediction System in use at the European Centre for Medium-Range Weather Forecasts) and COSMO-LEPS (Limited-area Ensemble Prediction System developed within COnsortium for Small-scale MOdelling) applied for power forecasts on a real case in Southern Italy is presented. The approach is based on retrieving meteorological ensemble variables (i.e. wind speed, wind direction), using them to create a power Probability Density Function (PDF) for each 0-72 h ahead forecast horizon. A statistical calibration of the ensemble wind speed members based on the use of past wind speed measurements is explained. The two models are compared using common verification indices and diagrams. The higher horizontal resolution model (COSMO-LEPS) shows slightly better performances, especially for lead times from 27 to 48 h ahead. For longer lead times the increase in resolution does not seem crucial to obtain better results. A deterministic application using the mean of each ensemble system is also presented and compared with a higher resolution 0-72 h ahead power forecast based on the ECMWF deterministic model. It is noticeable that, in a deterministic approach, a higher resolution of the ensemble system can lead to slightly better results that are comparable with those of the high resolution deterministic model.

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Contributors: Alessandrini, S., Sperati, S., Pinson, P.
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Source: dtu
Source ID: n:oai:DTIC-ART:compendex/384634384::27765
Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review
Chance-constrained optimization of demand response to price signals
Household-based demand response is expected to play an increasing role in supporting the large scale integration of renewable energy generation in existing power systems and electricity markets. While the direct control of the consumption level of households is envisaged as a possibility, a credible alternative is that of indirect control based on price signals to be sent to these end-consumers. A methodology is described here allowing to estimate in advance the potential response of flexible end-consumers to price variations, subsequently embedded in an optimal price-signal generator. In contrast to some real-time pricing proposals in the literature, here prices are estimated and broadcast once a day for the following one, for households to optimally schedule their consumption. The price-response is modeled using stochastic finite impulse response (FIR) models. Parameters are estimated within a recursive least squares (RLS) framework using data measurable at the grid level, in an adaptive fashion. Optimal price signals are generated by embedding the FIR models within a chance-constrained optimization framework. The objective is to keep the price signal as unchanged as possible from the reference market price, whilst keeping consumption below a pre-defined acceptable level.

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Contributors: Dorini, G. F., Pinson, P., Madsen, H.
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Controlling Electricity Consumption by Forecasting its Response to Varying Prices
In a real-time electricity pricing context where consumers are sensitive to varying prices, having the ability to anticipate their response to a price change is valuable. This paper proposes models for the dynamics of such price-response, and shows how these dynamics can be used to control electricity consumption using a one-way price signal. Estimation of the price-response is based on data measurable at grid level, removing the need to install sensors and communication devices between each individual consumer and the price-generating entity. An application for price-responsive heating systems is studied based on real data, before conducting a control by price experiment using a mixture of real and synthetic data. With the control objective of following a constant consumption reference, peak heating consumption is reduced by nearly 5%, and 11% of the mean daily heating consumption is shifted.

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Direct Interval Forecasting of Wind Power

This letter proposes a novel approach to directly formulate the prediction intervals of wind power generation based on extreme learning machine and particle swarm optimization, where prediction intervals are generated through direct optimization of both the coverage probability and sharpness, without the prior knowledge of forecasting errors. The proposed approach has been proved to be highly efficient and reliable through preliminary case studies using real-world wind farm data, indicating a high potential of practical application.

Discrimination ability of the Energy score

Research on generating and verification of multivariate probabilistic forecasts has gained increased interest over the last few years. Emphasis is placed here on the evaluation of forecast quality with the Energy score, which is based on a quadratic scoring rule. While this score may be seen as appealing since being proper, we show that its discrimination ability may be limited when focusing on the dependence structure of multivariate probabilistic forecasts. For the case of multivariate Gaussian process, a theoretical upper for such discrimination ability is derived and discussed. This limited discrimination ability may eventually get compromised by computational and sampling issues, as dimension increases.
Forecasting Electricity Spot Prices Accounting for Wind Power Predictions
A two-step methodology for forecasting of electricity spot prices is introduced, with focus on the impact of predicted system load and wind power generation. The nonlinear and nonstationary influence of these explanatory variables is accommodated in a first step based on a nonparametric and time-varying regression model. In a second step, time-series models, i.e., ARMA and Holt-Winters, are applied to account for residual autocorrelation and seasonal dynamics. Empirical results are presented for out-of-sample forecasts of day-ahead prices in the Western Danish price area of Nord Pool's Elspot, during a two year period covering 2010–2011. These results clearly demonstrate the practical benefits of accounting for the complex influence of these explanatory variables.

Forecasting Production Losses at a Swedish Wind Farm
Production loss due to icing has been identified as a problem both when siting turbines in cold climates, and when making forecasts of energy production for wind park management and energy markets. The Makkonen icing model (Makkonen, 2000), driven by output from the WRF mesoscale model, has been shown to predict periods of icing at a wind farm in northern Sweden (Davis et al, 2012) with improved skill compared to persistence and threshold models. Based on these results, we have developed a statistical model to estimate the loss of production at the wind park due to these icing periods. We compared this statistical model with a simpler method that does not rely on a physical icing model. In that method meteorological icing is identified as periods when WRF forecasts clouds and the temperature is below freezing. During these periods it is assumed that there is no production from the turbines, however as soon as the cloud goes away in the model we assume...
production returns to the idealized power curve. One unique aspect of the wind park we are working with is that it is not required to shut down when icing occurs. Therefore, during icing periods production still occurs, but below the idealized power curve. This enabled us to also examine how much production would have been lost had the turbines been required to shut down during the periods when they were iced.

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Contributors: Davis, N., Hahmann, A. N., Clausen, N., Zagar, M., Pinson, P.
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**Forecasting the conditional dynamic elasticity of electricity consumers**

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**Impact of Wind Power Generation on European Cross-Border Power Flows**
A statistical analysis is performed in order to investigate the relationship between wind power production and cross-border power transmission in Europe. A dataset including physical hourly cross-border power exchanges between European countries as dependent variables is used. Principal component analysis is employed in order to reduce the problem dimension. Then, nonlinear relationships between forecast wind power production as well as spot price in Germany, by far the largest wind power producer in Europe, and power flows are modeled using local polynomial regression. We find that both forecast wind power production and spot price in Germany have substantial nonlinear effects on power transmission on a European scale.

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Monitoring and characterizing offshore wind variability with weather radars for wind energy applications

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Pool Strategy of a Price-Maker Wind Power Producer
We consider the problem of a wind power producer trading energy in short-term electricity markets. The producer is a price-taker in the day-ahead market, but a price-maker in the balancing market, and aims at optimizing its expected revenues from these market floors. The problem is formulated as a mathematical program with equilibrium constraints (MPEC) and cast as a mixed-integer linear program (MILP), which can be solved employing off-the-shelf optimization software. The optimal bid is shown to deliver significantly improved performance compared to traditional bids such as the conditional mean or median forecast of wind power distribution. Finally, sensitivity analyses are carried out to assess the impact on the offering strategy of the producer’s penetration in the market, of the correlation between wind power production and residual system deviation, and of the shape of the forecast distribution of wind power production.

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Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Electrical Engineering, Center for Electric Power and Energy
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Pages: 3440-3450
Publication date: 2013
Peer-reviewed: Yes
Regime-based supervisory control to reduce power fluctuations from offshore wind power plants

Wind power fluctuations, especially offshore, can pose challenges in the secure and stable operation of the power system. In modern large offshore wind farms, there are supervisory controls designed to reduce the power fluctuations. Their operation is limited due to the fact that they imply loss of production, hence revenue for the wind farm operator. On the other hand, progresses in short term forecasting, together with the increasing use of probabilistic forecasting can help in achieving efficient power fluctuations reduction with minimum lost production. Here we present supervisory control concepts that consider different wind power regimes to derive control setpoints by using a Markov-Switching AutoRegressive model. We evaluate the performance versus measured data in terms of power ramp characteristics and energy efficiency.

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Contributors: Barahona Garzón, B., Cutululis, N. A., Trombe, P., Pinson, P.
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Renewable Energy Resources — Onshore/Offshore Wind Energy

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Contributors: Pinson, P., Giebel, G., Clausen, N.
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DOIs:
10.1016/B978-0-12-384703-4.00310-5
Space-time scenarios of wind power generation produced using a Gaussian copula with parametrized precision matrix

The emphasis in this work is placed on generating space-time trajectories (also referred to as scenarios) of wind power generation. This calls for prediction of multivariate densities describing wind power generation at a number of distributed locations and for a number of successive lead times. A modelling approach taking advantage of sparsity of precision matrices is introduced for the description of the underlying space-time dependence structure. The proposed parametrization of the dependence structure accounts for such important process characteristics as non-constant conditional precisions and direction-dependent cross-correlations. Accounting for the space-time effects is shown to be crucial for generating high quality scenarios.

Statistical Modelling of Wind Profiles - Data Analysis and Modelling

The aim of the analysis presented in this document is to investigate whether statistical models can be used to make very short-term predictions of wind profiles.

Stochastic power generation


Trading wind energy on the basis of probabilistic forecasts both of wind generation and of market quantities

Wind power is not easily predictable and non-dispatchable. Nevertheless, wind power producers are increasingly urged to participate in electricity market auctions in the same manner as conventional power producers. The aim of this paper is to propose an operational strategy for trading wind energy in liberalized electricity markets and to assess its performance. At first, the so-called optimal quantile strategy is revisited. It is proved that without market power, i.e. under the price-taker assumption, this strategy maximizes expected market revenues. Forecasts of wind power production, of day-ahead and real-time market prices and of the system imbalance are inputs to this strategy. Subsequently, constraining of the bid that maximizes the expected revenues is proposed as a way to overcome the strategy's disregard of practical limitations and, at the same time, of risk. Two constraining techniques are introduced: constraining in the decision space and in the probability space. Finally, the trade of a wind power producer is simulated in a test case for the Eastern Danish (DK-2) price area of the Nordic Power Exchange (Nord Pool) during a 10 month period in 2008. The results of the test case show the financial benefits of the aforementioned strategy as well as the consequent interaction with the electricity market. This study will support a demonstration in the framework of the EU project ANEMOS.plus.

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Contributors: Zugno, M., Jónsson, T., Pinson, P.
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Using forecast information for storm ride-through control

General information
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Organisations: Department of Wind Energy, Wind Energy Systems, Department of Applied Mathematics and Computer Science, Dynamical Systems, Meteorology, Center for Electric Power and Energy
Publication date: 2013
Using probabilistic forecast information in control algorithms can improve the performance of wind farms during periods of extreme winds. This work presents a wind farm supervisor control concept that uses probabilistic forecast information to ride-through a storm with softer ramps of power. Wind speed forecasts are generated with a statistical approach (i.e. time series models). The supervisor control is based on a set of logical rules that consider point forecasts and predictive densities to ramp-down the power of the wind farm before the storm hits. The potential of this supervisor control is illustrated with data from the Horns Rev 1 wind farm, located in the North Sea. To conclude, an overview of ongoing and future research in the Radar@Sea experiment is given. This experiment aims at improving offshore wind power predictability and controllability through the increased use of meteorological information, and particularly weather radar images.

Weather radars for wind energy applications

Wind Energy: Forecasting Challenges for its Operational Management

Renewable energy sources, especially wind energy, are to play a larger role in providing electricity to industrial and domestic consumers. This is already the case today for a number of European countries, closely followed by the US and high growth countries, e.g., Brazil, India and China. There exist a number of technological, environmental and political challenges linked to supplementing existing electricity generation capacities with wind energy. Here, mathematicians and statisticians could make a substantial contribution at the interface of meteorology and decision-making, in connection with the generation of forecasts tailored to the various operational decision problems involved. Indeed, while wind energy may
be seen as an environmentally friendly source of energy, full benefits from its usage can only be obtained if one is able to accommodate its variability and limited predictability. Based on a short presentation of its physical basics, the importance of considering wind power generation as a stochastic process is motivated. After describing representative operational decision-making problems for both market participants and system operators, it is underlined that forecasts should be issued in a probabilistic framework. Even though, eventually, the forecaster may only communicate single-valued predictions. The existing approaches to wind power forecasting are subsequently described, with focus on single-valued predictions, predictive marginal densities and space-time trajectories. Upcoming challenges related to generating improved and new types of forecasts, as well as their verification and value to forecast users, are finally discussed.

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Contributors: Pinson, P.
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- DOI: 10.1214/13-STS445
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Source ID: u::9612
Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review

**Adaptive calibration of (u,v)-wind ensemble forecasts**
Ensemble forecasts of (u,v)-wind are of crucial importance for a number of decision-making problems related to e.g. air traffic control, ship routing and energy management. The skill of these ensemble forecasts as generated by NWP-based models can be maximised by correcting for their lack of sufficient reliability. The original framework introduced here allows for an adaptive bivariate calibration of these ensemble forecasts. The originality of this methodology lies in the fact that
calibrated ensembles still consist of a set of (space–time) trajectories, after translation and dilation. In parallel, the
parameters of the models employed for improving the stochastic properties of the generating processes involved are
adaptively and recursively estimated to accommodate smooth changes in the process characteristics and to lower
computational costs. The approach is applied and evaluated based on the adaptive calibration of ECMWF ensemble
forecasts of (u,v)-wind at 10 m above ground level over Europe over a three-year period between December 2006 and
December 2009. Substantial improvements in (bivariate) reliability and in various deterministic/probabilistic scores are
observed. Finally, the maps of translation and dilation factors are discussed. Copyright © 2012 Royal Meteorological
Society

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Adaptive modelling and forecasting of offshore wind power fluctuations with Markov-switching autoregressive models
Wind power production data at temporal resolutions of a few minutes exhibit successive periods with fluctuations of
various dynamic nature and magnitude, which cannot be explained (so far) by the evolution of some explanatory variable.
Our proposal is to capture this regime-switching behaviour with an approach relying on Markov-switching autoregressive
(MSAR) models. An appropriate parameterization of the model coefficients is introduced, along with an adaptive
estimation method allowing accommodation of long-term variations in the process characteristics. The objective criterion
to be recursively optimized is based on penalized maximum likelihood, with exponential forgetting of past observations.
MSAR models are then employed for one-step-ahead point forecasting of 10 min resolution time series of wind power at
two large offshore wind farms. They are favourably compared against persistence and autoregressive models. It is finally
shown that the main interest of MSAR models lies in their ability to generate interval/density forecasts of significantly
higher skill.

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A General Probabilistic Forecasting Framework for Offshore Wind Power Fluctuations

Accurate wind power forecasts highly contribute to the integration of wind power into power systems. The focus of the present study is on large-scale offshore wind farms and the complexity of generating accurate probabilistic forecasts of wind power fluctuations at time-scales of a few minutes. Such complexity is addressed from three perspectives: (i) the modeling of a nonlinear and non-stationary stochastic process; (ii) the practical implementation of the model we propose; (iii) the gap between working on synthetic data and real world observations. At time-scales of a few minutes, offshore fluctuations are characterized by highly volatile dynamics which are difficult to capture and predict. Due to the lack of adequate on-site meteorological observations to relate these dynamics to meteorological phenomena, we propose a general model formulation based on a statistical approach and historical wind power measurements only. We introduce an advanced Markov Chain Monte Carlo (MCMC) estimation method to account for the different features observed in an empirical time series of wind power: autocorrelation, heteroscedasticity and regime-switching. The model we propose is an extension of Markov-Switching Autoregressive (MSAR) models with Generalized AutoRegressive Conditional Heteroscedastic (GARCH) errors in each regime to cope with the heteroscedasticity. Then, we analyze the predictive power of our model on a one-step ahead exercise of time series sampled over 10 min intervals. Its performances are compared to state-of-the-art models and highlight the interest of including a GARCH specification for density forecasts.
A Transmission-Cost-Based Model to Estimate the Amount of Market-Integrable Wind Resources

In the pursuit of the large-scale integration of wind power production, it is imperative to evaluate plausible frictions among the stochastic nature of wind generation, electricity markets, and the investments in transmission required to accommodate larger amounts of wind. If wind producers are made to share the expenses in transmission derived from their integration, they may see the doors of electricity markets closed for not being competitive enough. This paper presents a model to decide the amount of wind resources that are economically exploitable at a given location from a transmission-cost perspective. This model accounts for the uncertain character of wind by using a modeling framework based on stochastic optimization, simulates market barriers by means of a bi-level structure, and considers the financial risk of investments in transmission through the conditional value-at-risk. The major features of the proposed model, which is efficiently solved using Benders decomposition, are discussed through an illustrative example.

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Contributors: Morales González, J. M., Pinson, P., Madsen, H.
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Original language: English
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Research output: Contribution to journal › Journal article – Annual report year: 2012 › Research › peer-review

Early indication of extreme winds utilizing the Extreme Forecast Index

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http://www.ecmwf.int/publications/newsletters/
Source: dtu
Source ID: u::6086
Research output: Contribution to journal › Journal article – Annual report year: 2012 › Research › peer-review

Evaluating the quality of scenarios of short-term wind power generation

Scenarios of short-term wind power generation are becoming increasingly popular as input to multi-stage decision-making problems e.g. multivariate stochastic optimization and stochastic programming. The quality of these scenarios is intuitively
expected to substantially impact the benefits from their use in decision-making. So far however, their verification is almost always focused on their marginal distributions for each individual lead time only, thus overlooking their temporal interdependence structure. The shortcomings of such an approach are discussed. Multivariate verification tools, as well as diagnostic approaches based on event-based verification are then presented. Their application to the evaluation of various sets of scenarios of short-term wind power generation demonstrates them as valuable discrimination tools.
New statistical approaches with consideration for extremes

Probabilistic Forecasting of the Wave Energy Flux

Wave energy will certainly have a significant role to play in the deployment of renewable energy generation capacities. As with wind and solar, probabilistic forecasts of wave power over horizons of a few hours to a few days are required for power system operation as well as trading in electricity markets. A methodology for the probabilistic forecasting of the wave energy flux is introduced, based on a log-Normal assumption for the shape of predictive densities. It uses meteorological forecasts (from the European Centre for Medium-range Weather Forecasts – ECMWF) and local wave measurements as input. The parameters of the models involved are adaptively and recursively estimated. The methodology is evaluated for 13 locations around North-America over a period of 15months. The issued probabilistic forecasts substantially outperform the various benchmarks considered, with improvements between 6% and 70% in terms of Continuous Rank Probability Score (CRPS), depending upon the test case and the lead time. It is finally shown that the log-Normal assumption can be seen as acceptable, even though it may be refined in the future.
Risk Averse Bidding of Wind Power - Formulation and Properties

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Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics, Iowa State University
Contributors: Jónsson, T., Ryan, S. M., Zugno, M., Pinson, P.
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Research output: Book/Report › Report – Annual report year: 2012 › Research

In view of the increasing penetration of wind power in a number of power systems and markets worldwide, we discuss some of the impacts that wind energy may have on market quantities and cross-border power flows. These impacts are uncovered through statistical analyses of actual market and flow data in Europe. Due to the dimensionality and nonlinearity of these effects, the necessary concepts of dimension reduction using Principal Component Analysis (PCA), as well as nonlinear regression are described. Example application results are given for European cross-border flows, as well as for the impact of load and wind power forecasts on Danish and German electricity markets.

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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2012 › Research › peer-review
The use of different ensemble forecasting systems for wind power prediction on a real case in the South of Italy

Short-term forecasting applied to wind energy is becoming increasingly important due to the constant growth of this renewable source, whose uncertainty requires a constant effort to meet the needs of the national electrical systems and their operators. Regarding to this, the probabilistic approach applied to wind power forecasting (WPF) is showing an increasingly interest in terms of the possibility to reduce forecast errors, giving also a useful information on the accuracy of a forecast and a reliable estimation of its uncertainty; in fact, the prediction accuracy is not constant and often depends on the location of a certain wind farm, as well as on the atmospheric conditions of the site and the forecast horizon used.

According to previous studies of the same authors, the ECMWF Ensemble Prediction System (EPS) can be used as an indicator of a three-days ahead deterministic WPF accuracy. A statistical calibration performed on the wind speed EPS members allows an improvement from an over-confident situation observable from the rank histograms (in which the measurements fell quite always outside the bounds of the probability distribution) to a consistent ensemble spread. After that it is possible to convert the data to wind energy: the spread calculated on wind power can then be used as an accuracy predictor due to its level of correlation with the deterministic WPF error.

In this presentation we investigate the performances for both wind power and accuracy prediction of the new EPS used at the ECMWF, whose horizontal resolution was increased on January 2010 from 60 km to 32 km, on a complex terrain area already used in previous studies and located in Southern Italy. The work consists in the use of the ECMWF deterministic model in a WPF approach followed by a recursive feed-forward Neural Networks (NN) and finally by the application and verification of the EPS in order to estimate the forecast accuracy. We also preliminary compare these performances with the results obtainable from the application of other ensemble prediction systems with higher resolution.

Analyzing the results it can be seen that EPS calibration is a fundamental requirement in order to extract usable information from data; after an adequate calibration method, the ensemble spread calculated on wind power seems to have enough correlation with the deterministic forecast error in order to be used as a predictor of accuracy, at least until the three days ahead forecast horizon.

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Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics, Ricerca Sistema Energetico SpA
Contributors: Alessandrini, S., Sperati, S., Pinson, P.
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2012 › Research › peer-review
Verification of the ECMWF ensemble forecasts of wind speed against analyses and observations

A framework for the verification of ensemble forecasts of near-surface wind speed is described. It is based on existing scores and diagnostic tools, though considering observations from synoptic stations as reference instead of the analysis. This approach is motivated by the idea of having a user-oriented view of verification, for instance with the wind power applications in mind. The verification framework is specifically applied to the case of ECMWF ensemble forecasts and over Europe. Dynamic climatologies are derived at the various stations, serving as a benchmark. The impact of observational uncertainty on scores and diagnostic tools is also considered. The interest of this framework is demonstrated from its application to the routine evaluation of ensemble forecasts and to the assessment of the quality improvements brought in by the recent change in horizontal resolution of the ECMWF ensemble prediction system. The most important conclusions cover (1) the generally high skill of these ensemble forecasts of near-surface wind speed when evaluated at synoptic stations, (2) the noteworthy improvement of scores brought by the change of horizontal resolution, and, (3) the scope for further improvements of reliability and skill of wind speed ensemble forecasts by appropriate post-processing.

Very short-term probabilistic forecasting of wind power with generalized logit-Normal distributions

Very-short-term probabilistic forecasts, which are essential for an optimal management of wind generation, ought to account for the non-linear and double-bounded nature of that stochastic process. They take here the form of discrete–continuous mixtures of generalized logit–normal distributions and probability masses at the bounds. Both auto-regressive and conditional parametric auto-regressive models are considered for the dynamics of their location and scale.
parameters. Estimation is performed in a recursive least squares framework with exponential forgetting. The superiority of this proposal over classical assumptions about the shape of predictive densities, e.g. normal and beta, is demonstrated on the basis of 10-min-ahead point and probabilistic forecasting at the Horns Rev wind farm in Denmark.

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Weather radars - A new pair of eyes for offshore wind farms?

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Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics, Department of Wind Energy, Meteorology, DHI Water - Environment - Health, Danish Meteorological Institute, Ørsted A/S, Vattenfall Vindkraft A/S
Contributors: Trombe, P., Pinson, P., Vincent, C. L., Madsen, H., Jensen, N. E., Bevith, T., Le, N. F., Sommer, A.
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WIRE - Weather Intelligence for Renewable Energies

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Benefits from the increased contribution of the European weather forecasting community to wind power prediction

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Contributors: Pinson, P., Petrioliagis, T., Girard, R., Kariniotakis, G., Chavaux, F., Buizza, R.
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Can Weather Radars Help Monitoring and Forecasting Wind Power Fluctuations at Large Offshore Wind Farms?
The substantial impact of wind power fluctuations at large offshore wind farms calls for the development of dedicated monitoring and prediction approaches. Based on recent findings, a Local Area Weather Radar (LAWR) was installed at Horns Rev with the aim of improving predictability, controllability and potentially maintenance planning. Additional images are available from a Doppler radar covering the same area. The parallel analysis of rain events detection and of regime sequences in wind (and power) fluctuations demonstrates the interest of employing weather radars for a better operation and management of offshore wind farms.

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Contributors: Trombe, P., Pinson, P., Madsen, H., Jensen, N. E., Pedersen, L. B., Sommer, A., Le, N. F.
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Ensemble and probabilistic forecasting of (u,v)-wind for the energy application

Over the last decade, developments in the use of various renewable energy sources have been tremendous. Europe has been a pioneering region in opting for the large-scale deployment of wind energy, now being followed by solar and wave energy. Other countries like the United States, China, India and Brazil are catching up by giving increasing importance to renewable energies in their electricity generation mix. The common and maybe most important characteristics of these renewable energy sources is that their power generation depends upon atmospheric and marine conditions, with a stochastic behaviour embedding variability and potentially limited predictability. This forces substantial changes to the energy management and trading activities, which are to increasingly rely on high-quality meteorological forecasts for various lead times ranging from a few minutes to a few months, while evolving from a deterministic to a stochastic approach to decision-making. Early developments mainly concentrated on single-valued prediction every single wind farm, by post-processing deterministic forecasts of wind speed and direction (or alternatively wind in its (u; v) component form). Today ensemble and probabilistic forecasts are becoming increasingly popular among the actors of the power system and electricity markets. The energy application is particularly interesting since covering a variety of decision-making problems requiring different types of input forecasts. A few of them will be reviewed: it will be explained how some basic decision-making problems only require appropriately defined single-valued predictions that can be extracted from probabilistic forecasts, while some more advanced ones call for space-time (and possibly multivariate) trajectories, hence fully utilising the information given by ensemble forecasts. Anecdotal examples of irrational decision-making will also be given. The quality of wind power forecasts heavily depends upon that of the meteorological ones used as input. Ensemble forecasts of (u; v) wind should be calibrated before to input wind power prediction methodologies. But since their nature as space-time trajectories is crucial for a number of decision-making problems, focus is given to a multivariate calibration method which does not alter their nature. This method consists of translating and dilating ensemble forecasts based on models for the generating processes of the ensembles and the wind stochastic process. The parameters of these models are adaptively and recursively estimated, hence allowing for seasonal variations in the calibration while accommodating changes in the operational setup of the ensemble forecasting system considered. These model parameters are also seen as different for each model grid point. The overall methodology is applied and evaluated for the case of ECMWF ensemble forecasts of (u; v) wind over a period of 3 years (Dec. 2006 - Dec. 2009) and over Europe. The substantial improvements in the (bivariate) reliability of the ensemble forecasts, as well as for various deterministic and probabilistic scores, will be shown. Improvements in terms of CRPS and bivariate RMSE of the ensemble mean are substantial for lead times up to 3 days (10-25%) then fading out for lead times further than 5 days. The temporal and spatial patterns of the translation and dilation factors will finally be discussed.

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Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P.
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Forecasting ocean wave energy: A Comparison of the ECMWF wave model with time series methods

Recently, the technology has been developed to make wave farms commercially viable. Since electricity is perishable, utilities will be interested in forecasting ocean wave energy. The horizons involved in short-term management of power grids range from as little as a few hours to as long as several days. In selecting a method, the forecaster has a choice between physics-based models and statistical techniques. A further idea is to combine both types of models. This paper analyzes the forecasting properties of a well-known physics-based model, the European Center for Medium-Range Weather Forecasts (ECMWF) Wave Model, and two statistical techniques, time-varying parameter regressions and neural networks. Thirteen data sets at locations in the Atlantic and Pacific Oceans and the Gulf of Mexico are tested. The quantities to be predicted are the significant wave height, the wave period, and the wave energy flux. In the initial tests, the ECMWF model and the statistical models are compared directly. The statistical models do better at short horizons, producing more accurate forecasts in the 1–5 h range. The ECMWF model is superior at longer horizons. The convergence point, at which the two methods achieve comparable degrees of accuracy, is in the area of 6 h. By implication, the physics-based model captures the underlying signals at lower frequencies, while the statistical models...
capture relationships over shorter intervals. Further tests are run in which the forecasts from the ECMWF model are used as inputs in regressions and neural networks. The combined models yield more accurate forecasts than either one individually.

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- Web of Science (2011): Impact factor 1.178
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**Forecasting uncertainty around the timing of large variation of wind power**

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**Influence of local wind speed and direction on wind power dynamics – Application to offshore very short-term forecasting**

Wind power time series usually show complex dynamics mainly due to non-linearities related to the wind physics and the power transformation process in wind farms. This article provides an approach to the incorporation of observed local variables (wind speed and direction) to model some of these effects by means of statistical models. To this end, a benchmarking between two different families of varying coefficient models (regime-switching and conditional parametric models) is carried out. The case of the offshore wind farm of Horns Rev in Denmark has been considered. The analysis is focused on one-step ahead forecasting and a time series resolution of 10 min. It has been found that the local wind direction contributes to model some features of the prevailing winds, such as the impact of the wind direction on the wind variability, whereas the non-linearities related to the power transformation process can be introduced by considering the local wind speed. In both cases, conditional parametric models showed a better performance than the one achieved by the regime-switching strategy. The results attained reinforce the idea that each explanatory variable allows the modelling of different underlying effects in the dynamics of wind power time series.
Meso-scale Wind Variability. Final Report

The project has aimed to characterize mesoscale meteorological phenomenon for the North Sea and the Inner Danish waters, and additionally aimed on improving the predictability and quality of the power production from offshore windfarms. The meso-scale meteorology has been characterized with respect to the physical processes, climatology, spectral characteristics and correlation properties based on measurements from wind farms, satellite data (SAR) and mesoscale numerical modeling (WRF). The abilities of the WRF model to characterize and predict relevant mesoscale phenomenon has been proven. Additionally application of statistical forecasting, using a Markov switching approach that can be related to the meteorological conditions, to analyze and short term predict the power production from an offshore wind farms have been documented. Two PhD studies have been conducted in connection with the project. The project has been a cooperative project between Risø DTU, IMM DTU, DONG Energy, Vattenfall and VESTAS. It is registered as Energinet.dk, project no. 2007-1-7141.

General information
Publication status: Published
Contributors: Larsen, S. E., Larsén, X. G., Vincent, C. L., Sørensen, P. E., Pinson, P., Trombe, P., Madsen, H., Cutululis, N. A.
Number of pages: 114
Publication date: 2011

Publication information
Place of publication: Roskilde
Publisher: Danmarks Tekniske Universitet, Risø Nationalaboratorium for Bæredygtig Energi
ISBN (Print): 978-87-550-3937-7
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Electronic versions:
ris-r-1794.pdf
Radar@Sea - Towards improving short-term wind power forecasts

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Trombe, P., Pinson, P., Thomsen, S. C., Madsen, H.
Publication date: 2011
Peer-reviewed: No
Event: Poster session presented at European Geosciences Union General Assembly 2011, Vienna, Austria.
Electronic versions:
posterEGU_online_final_pjt.pdf
Source: orbit
Source ID: 276600
Research output: Contribution to conference › Poster – Annual report year: 2011 › Research

Scenario generation: A review

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Otterson, S., Madsen, H., Pinson, P., Jónsson, T.
Publication date: 2011
Publication information
Place of publication: Kgs. Lyngby, Denmark
Publisher: DTU Informatics, Building 305
Original language: English
Source: orbit
Source ID: 276987
Research output: Book/Report › Report – Annual report year: 2011 › Research

Spatio-temporal analysis and modeling of short-term wind power forecast errors
Forecasts of wind power production are increasingly being used in various management tasks. So far, such forecasts and related uncertainty information have usually been generated individually for a given site of interest (either a wind farm or a group of wind farms), without properly accounting for the spatio-temporal dependencies observed in the wind generation field. However, it is intuitively expected that, owing to the inertia of meteorological forecasting systems, a forecast error made at a given point in space and time will be related to forecast errors at other points in space in the following period. The existence of such underlying correlation patterns is demonstrated and analyzed in this paper, considering the case-study of western Denmark. The effects of prevailing wind speed and direction on autocorrelation and cross-correlation patterns are thoroughly described. For a flat terrain region of small size like western Denmark, significant correlation between the various zones is observed for time delays up to 5 h. Wind direction is shown to play a crucial role, while the effect of wind speed is more complex. Nonlinear models permitting capture of the interdependence structure of wind power forecast errors are proposed, and their ability to mimic this structure is discussed. The best performing model is shown to explain 54% of the variations of the forecast errors observed for the individual forecasts used today. Even though focus is on 1-h-ahead forecast errors and on western Denmark only, the methodology proposed may be similarly tested on the cases of further look-ahead times, larger areas, or more complex topographies. Such generalization may not be straightforward. While the results presented here comprise a first step only, the revealed error propagation principles may be seen as a basis for future related work.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Tastu, J., Pinson, P., Kotwa, E., Madsen, H., Nielsen, H. A.
Pages: 43-60
Publication date: 2011
Peer-reviewed: Yes
Publication information
Journal: Wind Energy
Spatio-temporal correction targeting Nysted Offshore. Probabilistic forecasts

This report concerns probabilistic forecasts for Nysted Offshore. Different approaches for issuing predictive densities are studied, discussed in details and compared. The results show that the spatial correction of the first order moments of the predictive densities improves the quality of the corresponding forecasts. The spatial correction of the higher order moments is shown to be unnecessary as does not bring any additional amelioration. The best performing of the studied models is based on the adaptive quantile regression using the spatially corrected point predictions as input. This model is shown to outperform the benchmark approach in terms of the CRPS score (accuracy measure) by 1.5%-8.29% depending on the considered prediction horizon.

General information
Publication status: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics
Contributors: Tastu, J., Pinson, P., Trombe, P., Madsen, H.
Number of pages: 33
Publication date: 2011

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark (DTU)
Original language: English
(DTU Compute-Technical Report-2013; No. 16).
Electronic versions:
tr13_16_Tastu_Pinson_Trombe_Madsen.pdf

The influence of the new ECMWF Ensemble Prediction System resolution on wind power forecast accuracy and uncertainty estimation

The importance of wind power forecasting (WPF) is nowadays commonly recognized because it represents a useful tool to reduce problems of grid integration and to facilitate energy trading. If on one side the prediction accuracy is fundamental to these scopes, on the other it has become also clear that a reliable estimation of their uncertainty could be a useful information too. In fact the prediction accuracy is unfortunately not constant and can depend on the location of a particular wind farm, on the forecast time and on the atmospheric situation. Previous studies indicated that the ECMWF Ensemble Prediction System (EPS) can be used as indicator of a three-hourly, three days ahead, wind power forecast’s accuracy. In particular it has been noticed that to extract usable information from data the Ensemble members needed to be statistically calibrated, since the rank histograms for the three-day period showed an overconfident model: in other words we observed that the measurements fell quite always outside the bounds of the probability distribution, with the result that the first and the last intervals were the most populated (U-shaped distribution of the rank histogram). This situation was improved by a recalibration procedure that allowed obtaining a more uniform distribution among the 51 intervals, making the ensemble spread large enough to include the observations. After that it was observed that the EPS power spread seemed to have enough correlation with the error calculated on the deterministic forecast in order to be used as an accuracy predictor. In this paper we show the results of a new application of the EPS, whose horizontal resolution was increased from T399/T255 (60 km) to T639/T319 (32 km) on January 2010, on the same site of previous studies: a complex terrain area located in Southern Italy. Using more recent data, from October 22, first we focus our attention on the influence of the new EPS configuration on the performances of the deterministic WPF obtainable from the ensemble mean. We also compare
these performances with those obtainable by using high resolution meteorological models like RAMS. Then we analyse how both prediction accuracy and related uncertainty information are enhanced by using the new EPS resolution.

**General information**
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Ricerca Sistema Energetico SpA
Contributors: Alessandrini, S., Pinson, P., Sperati, S., Decimi, G.
Publication date: 2011

**Host publication information**
Title of host publication: EMS Annual Meeting Abstracts
Volume: 8

**Wind fluctuations over the North Sea**
Climatological patterns in wind speed fluctuations with periods of 1 min to 10 h are analysed using data from a meteorological mast in the Danish North Sea. Fluctuations on these time scales are of particular relevance to the effective management of the power supply from large wind farms. The Hilbert-Huang transform (HHT) is shown to be an effective tool for analysing long time series of wind speed observations, as it describes the time-evolving spectral information in the time series. By binning and averaging the time-evolving spectrum, the average spectral behaviour of the wind speed under a certain class of conditions can be found. Here, the HHT is applied to create conditional spectra which demonstrate patterns in the occurrence of severe wind variability. It is shown that wind fluctuations over the North Sea are more severe for westerly flow than for easterly flow, and that severe fluctuations are often observed in the vicinity of precipitation. The most severe wind fluctuations occur in the autumn and winter seasons, and are slightly more common when the pressure tendency is rising. Further, it is found that the wind is more variable for atmospherically unstable conditions than for stable conditions. Copyright © 2010 Royal Meteorological Society

**General information**
Publication status: Published
Organisations: Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Vincent, C. L., Pinson, P., Giebel, G.
Pages: 1584-1595
Publication date: 2011
Peer-reviewed: Yes

**Publication information**
Journal: International Journal of Climatology
Volume: 31
Issue number: 11
ISSN (Print): 0899-8418
Ratings:
  BFI (2011): BFI-level 1
  Scopus rating (2011): CiteScore 2.85 SJR 1.842 SNIP 1.606
  Web of Science (2011): Impact factor 2.906
  ISI indexed (2011): ISI indexed yes
  Web of Science (2011): Indexed yes
Original language: English
Keywords: Wind power meteorology, Wind Energy
DOIs: 10.1002/joc.2175
Source: orbit
Source ID: 269406
Research output: Contribution to journal › Journal article – Annual report year: 2010 › Research › peer-review
An application of ensemble/multi model approach for wind power production forecast

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Alessandrini, S., Pinson, P., Hagedorn, R., Decimi, G., Sperati, S.
Publication date: 2010

Host publication information
Title of host publication: Proc. of the 2010 European Meteorological Society Conference, Zurick, Switzerland
Source: orbit
Source ID: 270943
Research output: Chapter in Book/Report/Conference proceeding » Article in proceedings – Annual report year: 2010 » Research

Conditional prediction intervals of wind power generation

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Ecole des Mines de Paris
Contributors: Pinson, P., Kariniotakis, G.
Pages: 1845-1856
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: IEEE Transactions on Power Systems
Volume: 25
Issue number: 4
ISSN (Print): 0885-8950
Ratings:
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.708 SNIP 2.746
Web of Science (2010): Impact factor 2.355
Web of Science (2010): Indexed yes
Original language: English
Electronic versions:
pinson09_predints_rev.pdf
DOIs:
10.1109/TPWRS.2010.2045774
Source: orbit
Source ID: 247505
Research output: Contribution to journal » Journal article – Annual report year: 2010 » Research » peer-review

Conditional Weighted Combination of Wind Power Forecasts

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Thordarson, F. Ø., Madsen, H., Nielsen, H. A., Pinson, P.
Pages: 751-763
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Wind Energy
Volume: 13
Issue number: 8
ISSN (Print): 1095-4244
Ratings:
BFI (2010): BFI-level 2
Decision making strategies for trading wind power in deregulated energy markets

General information
Publication status: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics
Contributors: Zugno, M., Pinson, P., Jónsson, T.
Publication date: 2010

Host publication information
Title of host publication: IAEE'S Rio 2010 International Conference Proceedings
Source: orbit
Source ID: 270948
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2010

Defining a catalogue of extreme events

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P.
Publication date: 2010

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference, EWEC 2010
Source: orbit
Source ID: 257114
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2010

Feedback, competition and stochasticity in a day ahead electricity market

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Giabardo, P., Zugno, M., Pinson, P., Madsen, H.
Pages: 292-301
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Energy Economics
Volume: 32
Issue number: 2
ISSN (Print): 0140-9883
Ratings:
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 2.05 SNIP 1.978
Web of Science (2010): Impact factor 2.466
Web of Science (2010): Indexed yes
Original language: English
Electronic versions:
Idealised simulations of open cellular convection and horizontal wind fluctuations over the North Sea

General information
Publication status: Published
Organisations: Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Vincent, C. L., Hahmann, A. N., Pinson, P., Giebel, G.
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Geophysical Research Abstracts
Issue number: EGU2010-11025
ISSN (Print): 1607-7962
Original language: English
Keywords: Wind power meteorology, Wind Energy
Electronic versions:
EGU2010-11025.pdf
Source: orbit
Source ID: 271133
Research output: Contribution to journal › Conference article – Annual report year: 2010 › Research › peer-review

Multivariate conditional parametric models for a spatio-temporal analysis of short-term wind power forecast errors

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Tastu, J., Pinson, P., Madsen, H.
Publication date: 2010

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference, EWEC 2010
Source: orbit
Source ID: 257115
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research › peer-review

On probabilistic forecasting of wind power time-series

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P.
Publication date: 2010

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark, DTU Informatics, Building 321
Original language: English
(IMM-Technical Report-2010-06).
Electronic versions:
tr10_06-vers2.pdf
Source: orbit
Source ID: 259984
Research output: Book/Report › Report – Annual report year: 2010 › Research
On the market impact of wind energy forecasts

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Jónsson, T., Pinson, P., Madsen, H.
Pages: 313-320
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Energy Economics
Volume: 32
Issue number: 2
ISSN (Print): 0140-9883
Ratings:
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 2.05 SNIP 1.978
Web of Science (2010): Impact factor 2.466
Web of Science (2010): Indexed yes
Original language: English
Electronic versions:
Jonsson09_impact.pdf
DOIs:
10.1016/j.eneco.2009.10.018
Source: orbit
Source ID: 237855
Research output: Contribution to journal › Journal article – Annual report year: 2010 › Research › peer-review

On the Market Impact of Wind Power (Forecasts) - An Overview of the Effects of Large-scale Integration of Wind Power on the Electricity Market

General information
Publication status: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics
Contributors: Jónsson, T., Zugno, M., Madsen, H., Pinson, P.
Publication date: 2010

Host publication information
Title of host publication: IAEE’S Rio 2010 International Conference Proceedings
Source: orbit
Source ID: 270949
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research › peer-review

Prediction of extreme wind events by utilisation of a weather-type Extreme Forecast Index - Part I: Early warnings of extreme wind events utilizing DWD objective weather type classification & ECMWF Ensemble Prediction System Extreme Forecast Index

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Petroliagis, T., Jacques-Coper, M., von Bremen, L., Hagedorn, R., Pinson, P., Heinemann, D.
Publication date: 2010

Host publication information
Title of host publication: Proc. of the 2010 DEWEK Conference, German Wind Energy Conference
Source: orbit
Source ID: 271015
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research
Reliability diagrams for non-parametric density forecasts of continuous variables: Accounting for serial correlation

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, University of Oxford
Contributors: Pinson, P., McSharry, P., Madsen, H.
Pages: 77-90
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Quarterly Journal of the Royal Meteorological Society
Volume: 136
Issue number: 646
ISSN (Print): 0035-9009
Ratings:
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 2.429 SNIP 1.215
Web of Science (2010): Impact factor 2.977
Web of Science (2010): Indexed yes
Original language: English
Electronic versions:
pinsonetal09_reliability_rev.pdf
DOIs:
10.1002/qj.559
Source: orbit
Source ID: 244610
Research output: Contribution to journal › Journal article – Annual report year: 2010 › Research › peer-review

Resolving Nonstationary Spectral Information in Wind Speed Time Series Using the Hilbert-Huang Transform
This work is motivated by the observation that large-amplitude wind fluctuations on temporal scales of 1–10 h present challenges for the power management of large offshore wind farms. Wind fluctuations on these scales are analyzed at a meteorological measurement mast in the Danish North Sea using a 4-yr time series of 10-min wind speed observations. An adaptive spectral analysis method called the Hilbert–Huang transform is chosen for the analysis, because the nonstationarity of time series of wind speed observations means that they are not well described by a global spectral analysis method such as the Fourier transform. The Hilbert–Huang transform is a local method based on a nonparametric and empirical decomposition of the data followed by calculation of instantaneous amplitudes and frequencies using the Hilbert transform. The Hilbert–Huang transformed 4-yr time series is averaged and summarized to show climatological patterns in the relationship between wind variability and time of day. First, by integrating the Hilbert spectrum along the frequency axis, a scalar time series representing the total variability within a given frequency range is calculated. Second, by calculating average spectra conditional to time of day, the time axis of the Hilbert spectrum is “remapped” to show climatological patterns. Third, the daily patterns in wind variability and wind speed are compared for the four seasons of the year. It is found that the most intense wind variability occurs in autumn even though the strongest observed wind speeds occur in winter.

General information
Publication status: Published
Organisations: Wind Energy Educational Programme, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Meteorology, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Vincent, C. L., Giebel, G., Pinson, P., Madsen, H.
Pages: 253-267
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Journal of Applied Meteorology and Climatology
Volume: 49
Issue number: 2
ISSN (Print): 1558-8424
Ratings:
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.822 SNIP 1.207
Trading wind energy in a liberalized electricity market: a real-world test case in Eastern Denmark

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Zugno, M., Jónsson, T., Pinson, P.
Publication date: 2010

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference, EWEC 2010
Source: orbit
Source ID: 257118
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2010 – Research

Adaptive modelling and forecasting of offshore wind power fluctuations with Markov-switching autoregressive models

Wind power production data at temporal resolutions of a few minutes exhibits successive periods with fluctuations of various dynamic nature and magnitude, which cannot be explained (so far) by the evolution of some explanatory variable. Our proposal is to capture this regime-switching behaviour with an approach relying on Markov-Switching AutoRegressive (MSAR) models. An appropriate parameterization of the model coefficients is introduced, along with an adaptive estimation method allowing to accommodate long-term variations in the process characteristics. The objective criterion to be recursively optimized is based on penalized maximum-likelihood, with exponential forgetting of past observations. MSAR models are then employed for 1-step-ahead point forecasting of 10-minute resolution time-series of wind power at two large offshore wind farms. They are favourably compared against persistence and AutoRegressive (AR) models. It is finally shown that the main interest of MSAR models lies in their ability to generate interval/density forecasts of significantly higher skill.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Madsen, H.
Publication date: 2009

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Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark, DTU Informatics, Building 321
Original language: English
Source: orbit
Source ID: 251356

Catalogue of complex to extreme situations

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P.
Publication date: 2009

Publication information
Characterisation of wind variability at the Horns Reef wind farm

General information
Publication status: Published
Organisations: Wind Energy Educational Programme, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Meteorology, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Vincent, C. L., Giebel, G., Pinson, P.
Pages: 179-183
Publication date: 2009

Host publication information
Title of host publication: EWEC 2009 Scientific proceedings
Publisher: EWEC
Keywords: Wind energy, Meteorology
Source: orbit
Source ID: 240456

Communication of wind power forecast uncertainty: towards a standard

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Pinson, P., Madsen, H., Nielsen, H. A. O. T. 3., Nielsen, T. S., Giebel, G., Lange, M.
Publication date: 2009

Publication information
Original language: English
(EU project Anemos.plus, Deliverable Report D-1.10).
Keywords: Wind energy, Meteorology
Electronic versions:
anemos.plus.deliverable_D-1.10.pdf
Source: orbit
Source ID: 251724
Research output: Book/Report › Report – Annual report year: 2009 › Research

Dynamic sizing of energy storage for hedging wind power forecast uncertainty
In market conditions where program responsible parties are penalized for deviations from proposed bids, energy storage can be used for compensating the energy imbalances induced by limited predictability of wind power. The energy storage capacity necessary for performing this task will differ between delivery periods, according to the magnitude and the evolution of forecast errors in each delivery period. A methodology is presented for the assessment of the necessary storage capacity for each delivery period, based on the degree of risk that the power producer accepts to be exposed to. This approach leads to a dynamic assessment of the energy storage capacity for different delivery periods. In such a context, energy storage is used as a means of risk hedging against penalties from the regulation market. The application of the algorithm on real data (both measurements and forecasts) of the yearly output of a wind farm shows that the application of a dynamic daily sizing of the necessary storage leads to a significant reduction of the storage capacity used, without affecting the producer's profit significantly. The method proposed here may provide the basis for the introduction of storage as an independent market entity, where each producer may rent the necessary daily storage capacity for hedging the risk of the wind power limited predictability.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Ecofys Germany GmbH, Austrian Power Grid AG, Siemens
Contributors: Pinson, P., Papefthymiou, G., Klöckl, B., Verboomen, J.
Pages: 1-8
Effects of increasing wind power penetration on the physical operation of large electricity market systems

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Klöckl, B., Pinson, P.
Publication date: 2009

Host publication information
Title of host publication: Proc. of the CIGRE 2009
Electronic versions:
KloecklPinson_CIGRE09.pdf
Source: orbit
Source ID: 239541

Ensemble-based forecasting at Horns Rev: Ensemble conversion and kernel dressing
For management and trading purposes, information on short-term wind generation (from few hours to few days ahead) is even more crucial at large offshore wind farms, since they concentrate a large capacity at a single location. The most complete information that can be provided today consists of probabilistic forecasts, the resolution of which may be maximized by using meteorological ensemble predictions as input. The paper concentrates on the test case of the Horns Rev wind farm over a period of approximately one year, in order to describe, apply and discuss a complete ensemble-based forecasting methodology. In a first stage, ensemble forecasts of meteorological variables are converted to power through a suitable power curve model. The relevance and benefits of employing a newly developed orthogonal fitting method for the power curve model over the traditional least-squares one are discussed. The obtained ensemble forecasts of wind power are then converted into predictive distributions with an original adaptive kernel dressing method. The shape of the kernels is driven by a mean-variance model, the parameters of which are recursively estimated in order to maximize the overall skill of obtained predictive distributions. Such a methodology has the benefit of yielding predictive distributions that are of increased reliability (in a probabilistic sense) in comparison with the raw ensemble forecasts, while taking advantage of their high resolution.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Madsen, H.
Publication date: 2009

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Place of publication: Lyngby
Publisher: Technical University of Denmark, DTU Informatics, Building 321
Original language: English
Source: orbit
Ensemble-based Probabilistic Forecasting at Horns Rev

For management and trading purposes, information on short-term wind generation (from a few hours to a few days ahead) is crucial at large offshore wind farms, since they concentrate a large capacity at a single location. The most complete information that can be provided today consists of probabilistic forecasts, the resolution of which may be maximized by using meteorological ensemble predictions as input. The paper concentrates on the test case of the Horns Rev wind farm over a period of approximately 1 year, in order to describe, apply and discuss a complete ensemble-based probabilistic forecasting methodology. In a first stage, ensemble forecasts of meteorological variables are converted to power through a suitable power curve model. This model employs local polynomial regression, and is adaptively estimated with an orthogonal fitting method. The obtained ensemble forecasts of wind power are then converted into predictive distributions with an original adaptive kernel dressing method. The shape of the kernels is driven by a mean-variance model, the parameters of which are recursively estimated in order to maximize the overall skill of obtained predictive distributions. Such a methodology has the benefit of yielding predictive distributions that are of increased reliability (in a probabilistic sense) in comparison with the raw ensemble forecasts, at the same time taking advantage of their high resolution. 

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Forecasting day-ahead electricity prices and regulation costs in markets with significant wind power penetration

From probabilistic forecasts to statistical scenarios of short-term wind power production

Short-term (up to 2-3 days ahead) probabilistic forecasts of wind power provide forecast users with highly valuable information on the uncertainty of expected wind generation. Whatever the type of these probabilistic forecasts, they are produced on a per horizon basis, and hence do not inform on the development of the forecast uncertainty through forecast series. However, this additional information may be paramount for a large class of time-dependent and multistage
decision-making problems, e.g. optimal operation of combined wind-storage systems or multiple-market trading with different gate closures. This issue is addressed here by describing a method that permits the generation of statistical scenarios of short-term wind generation that accounts for both the interdependence structure of prediction errors and the predictive distributions of wind power production. The method is based on the conversion of series of prediction errors to a multivariate Gaussian random variable, the interdependence structure of which can then be summarized by a unique covariance matrix. Such matrix is recursively estimated in order to accommodate long-term variations in the prediction error characteristics. The quality and interest of the methodology are demonstrated with an application to the test case of a multi-MW wind farm over a period of more than 2 years.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Papaefthymiou, G., Klockl, B., Nielsen, H. A., Madsen, H.
Pages: 51-62
Publication date: 2009
Peer-reviewed: Yes

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Journal: Wind Energy
Volume: 12
Issue number: 1
ISSN (Print): 1095-4244
Ratings:
BFI (2009): BFI-level 2
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Web of Science (2009): Indexed yes
Original language: English
Keywords: forecasting, multivariate Gaussian random variable, scenarios, uncertainty, wind power
Electronic versions:
pinsonetal_wpfscenarios_fin.pdf
DOIs:
10.1002/we.284
Source: orbit
Source ID: 209942
Research output: Contribution to journal › Journal article – Annual report year: 2009 › Research › peer-review

Modelling and Forecasting of wind power fluctuations at large offshore wind farms.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Trombe, P., Pinson, P.
Publication date: 2009

Event information
Event: European Offshore Wind Conference 2009
Location: Stockholm, Swaziland
Source: orbit
Source ID: 257351
Research output: Non-textual form › Sound/Visual production (digital) – Annual report year: 2009 › Research

Modelling and Forecasting of wind power fluctuations using Markov-Switching AR-GARCH models.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Trombe, P., Pinson, P.
Publication date: 2009

Event information
Event: International Symposium on Forecasting
Location: Hong Kong
Source: orbit
Source ID: 257349
On the reliability assessment of density forecasts of continuous variables with reliability diagrams

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, University of Oxford
Contributors: Pinson, P., McSharry, P., Madsen, H.
Publication date: 2009

Host publication information
Title of host publication: Proc. of the International Symposium on Forecasting 2009
Source: orbit
Source ID: 239540
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2009 – Research

Power fluctuations from large wind farms - Final report
Experience from power system operation with the first large offshore wind farm in Denmark: Horns Rev shows that the power from the wind farm is fluctuating significantly at certain times, and that this fluctuation is seen directly on the power exchange between Denmark and Germany. This report describes different models for simulation and prediction of wind power fluctuations from large wind farms, and data acquired at the two large offshore wind farms in Denmark are applied to validate the models. Finally, the simulation model is further developed to enable simulations of power fluctuations from several wind farms simultaneously in a larger geographical area, corresponding to a power system control area.

General information
Publication status: Published
Number of pages: 49
Publication date: 2009

Publication information
Place of publication: Roskilde
Publisher: Danmarks Tekniske Universitet, Risø National laboratoriet for Bæredygtig Energi
ISBN (Print): 978-87-550-3782-3
Original language: English
Keywords: Wind energy systems, Wind energy, Risø-R-1711, Risø-R-1711(EN)
Electronic versions:
ris-r-1711.pdf
Source: orbit
Source ID: 248594

Prediction of waves, wakes and offshore wind - the results of the POWWOW project
General information
Publication status: Published
Organisations: Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Instituto National de Engenharia e Tecnologia Industrial, Institut für Solarenergieforschung
Publication date: 2009

Host publication information
Title of host publication: EWEC 2009 Proceedings online
Publisher: EWEC
Keywords: Wind energy, Meteorology
Electronic versions:
Skill forecasting from ensemble predictions of wind power

Optimal management and trading of wind generation calls for the providing of uncertainty estimates along with the commonly provided short-term wind power point predictions. Alternative approaches for the use of probabilistic forecasting are introduced. More precisely, focus is given to prediction risk indices aiming to give a comprehensive signal on the expected level of forecast uncertainty. Ensemble predictions of wind generation are used as input. A proposal for the definition of prediction risk indices is given. Such skill forecasts are based on the spread of ensemble forecasts (i.e. a set of alternative scenarios for the coming period) for a single prediction horizon or over a look-ahead period. It is shown on the test case of a Danish offshore wind farm how these prediction risk indices may be related to several levels of forecast uncertainty (and potential energy imbalances). Wind power ensemble predictions are derived from the conversion of ECMWF and NCEP ensemble forecasts of meteorological variables to wind power ensemble forecasts, as well as by a lagged average approach alternative. The ability of prediction risk indices calculated from the various types of ensembles forecasts to resolve among situations with different levels of uncertainty is discussed.

Spectral verification of a mesoscale ensemble

General information
Publication status: Published
Contributors: Vincent, C. L., Draxl, C., Giebel, G., Pinson, P., Jørgensen, J., Möhrlen, C.
Publication date: 2009

Host publication information
Title of host publication: EWEC 2009 Proceedings online
Publisher: EWEC
Keywords: Wind energy, Meteorology
Electronic versions:
2009_15.pdf
Source: orbit
Source ID: 243723
Research output: Contribution to journal › Journal article – Annual report year: 2009 › Research › peer-review
Temperature prediction at critical points in district heating systems

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Nielsen, T. S., Nielsen, H. A., Poulsen, N. K., Madsen, H.
Pages: 163-176
Publication date: 2009
Peer-reviewed: Yes

Publication information
Journal: European Journal of Operational Research
Volume: 194
Issue number: 1
ISSN (Print): 0377-2217
Ratings:
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 2.236 SNIP 2.584
Web of Science (2009): Indexed yes
Original language: English
Electronic versions:
pinsonetal_temppred_rev2.pdf
DOI:
10.1016/j.ejor.2007.11.065
Source: orbit
Source ID: 209974
Research output: Contribution to journal › Journal article – Annual report year: 2009 › Research › peer-review

Variability forecasts for wind farms using high resolution initial conditions

General information
Publication status: Published
Organisations: Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Draxl, C., Vincent, C. L., Hahmann, A. N., Giebel, G., Pinson, P.
Number of pages: 740
Pages: 719-724
Publication date: 2009

Host publication information
Title of host publication: Proceedings
Publisher: Energynautics GmbH
Editors: Betancourt, U., Ackermann, T.
Keywords: Wind energy, Meteorology
Source: orbit
Source ID: 251361
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2009 › Research

Best practice in the use of short-term forecasting - Results from 2 workshops organized by the POWWOW Coordination Action

General information
Publication status: Published
Contributors: Giebel, G., Pinson, P., Fochen, U., Lange, M., Meyer, R., Kariniotakis, G.
Publication date: 2008
Ecogrid.dk Phase 1 WP4 report: New measures for integration of large scale renewable energy

General information
Publication status: Published
Publication date: 2008

Forecasting of wind generation: recent advances and future challenges

General information
Publication status: Published
Publication date: 2008

Forecasting of wind generation - The wind power of tomorrow on your screen today!

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Pinson, P., Giebel, G., Madsen, H.
Pages: 32-35
Publication date: 2008
Peer-reviewed: Unknown

Publication information
Journal: Windtech International
Volume: 4
Issue number: 8
ISSN (Print): 1574-2415
Original language: English
Source: orbit
Forecasting the potential magnitude of power fluctuations at large offshore wind farms with an adaptive Markov-switching approach

General information
Publication status: Published
Contributors: Pinson, P., Madsen, H., Sørensen, P. E., Kristoffersen, J. R., Jensen, L. E.
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference 2008 : (Scientific Track)
Source: orbit
Source ID: 223282
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2008 › Research › peer-review

From meteorological ensembles to reliable probabilistic forecasts of wind generation

General information
Publication status: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics
Contributors: Pinson, P., Madsen, H.
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the 28th Annual International Symposium on Forecasting
Source: orbit
Source ID: 223287
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2008 › Research

HRensembleHR project progress in applying short-range ensemble forecasts for offshore wind power

General information
Publication status: Published
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference 2008
Source: orbit
Source ID: 223276
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2008 › Research

HRensemble project progress in applying short-range ensemble forecasts for offshore wind power

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Publication date: 2008
Local linear regression with adaptive orthogonal fitting for the wind power application

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Nielsen, H. A., Madsen, H., Nielsen, T. S.
Pages: 59-71
Publication date: 2008
Peer-reviewed: Yes

Publication information
Journal: Statistics and Computing
Volume: 18
Issue number: 1
ISSN (Print): 0960-3174
Ratings:
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.94 SNIP 1.203
Web of Science (2008): Indexed yes
Original language: English
Electronic versions:
pinsonetal_llr_orfift_wapp_rev.pdf
DOIs:
10.1007/s11222-007-9038-7
Source: orbit
Source ID: 209265
Research output: Contribution to journal › Journal article – Annual report year: 2008 › Research › peer-review

Modeling of spatial dependence in wind power forecast uncertainty

It is recognized today that short-term (up to 2-3 days ahead) probabilistic forecasts of wind power provide forecast users with a paramount information on the uncertainty of expected wind generation. When considering different areas covering a region, they are produced independently, and thus neglect the interdependence structure of prediction errors, induced by movement of meteorological fronts, or more generally by inertia of meteorological systems. This issue is addressed here by describing a method that permits to generate interdependent scenarios of wind generation for spatially distributed wind power production for specific look-ahead times. The approach is applied to the case of western Denmark split in 5 zones, for a total capacity of more than 2.1 GW. The interest of the methodology for improving the resolution of probabilistic forecasts, for a range of decision-making problems, or simply for better understanding the characteristics of forecast uncertainty, is discussed.

General information
Publication status: Published
Organisations: Department of Informatics and Mathematical Modeling, Mathematical Statistics, Delft University of Technology
Contributors: Papaefthymiou, G., Pinson, P.
Pages: 1-9
Publication date: 2008

Host publication information
Title of host publication: Proceedings of IEEE PMAPS 2008, 'Probabilistic Methods Applied to power Systems'
Publisher: IEEE
ISBN (Print): 978-1-9343-2521-6
Electronic versions:
Papaefthymiou-Spatial_dependence_in_wind_power_forecast_uncertainty.pdf
Source: orbit
Source ID: 223286
Modelling of power fluctuations from large offshore wind farms

This paper deals with modelling of power fluctuations from large wind farms. The modelling is supported and validated using wind speed and power measurements from the two large offshore wind farms in Denmark. The time scale in focus is from 1 min to a couple of hours, where significant power fluctuations have been observed from these wind farms. Power and wind speed are measured with 1 s sampling time in all individual wind turbines in almost 1 year, which provides a substantial database for the analyses. The paper deals with diversified models representing each wind turbine individually and with aggregation of a wind farm to be represented by a single large wind turbine model. Copyright (C) 2007 John Wiley & Sons, Ltd.

General information
Publication status: Published
Pages: 29-43
Publication date: 2008
Peer-reviewed: Yes

Publication information
Journal: Wind Energy
Volume: 11
Issue number: 1
ISSN (Print): 1095-4244
Ratings:
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 0.743 SNIP 1.522
Web of Science (2008): Indexed yes
Original language: English
DOIs:
10.1002/we.246
Source: orbit
Source ID: 220608
Research output: Contribution to journal › Journal article – Annual report year: 2008 › Research › peer-review

Modelling the nonlinear temperature response of district heating systems for model predictive control applications

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the 11th International Symposium on District Heating and Cooling
Source: orbit
Source ID: 223288
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2008 › Research › peer-review

POW'WOW - Workshops and virtual laboratories supporting wind research

General information
Publication status: Published
Contributors: Giebel, G., Barthelmie, R. J., Sempreviva, A. M., Sood, A., Lange, B., Pinson, P., Perez, I., Kariniotakis, G., Pontes, T., Rosas, P., Pereira, A.
Probabilistic forecasting of wind power at the minute time-scale with Markov-switching autoregressive models

Better modelling and forecasting of very short-term power fluctuations at large offshore wind farms may significantly enhance control and management strategies of their power output. The paper introduces a new methodology for modelling and forecasting such very short-term fluctuations. The proposed methodology is based on a Markov-switching autoregressive model with time-varying coefficients. An advantage of the method is that one can easily derive full predictive densities. The quality of this methodology is demonstrated from the test case of 2 large offshore wind farms in Denmark. The exercise consists in 1-step ahead forecasting exercise on time-series of wind generation with a time resolution of 10 minute. The quality of the introduced forecasting methodology and its interest for better understanding power fluctuations are finally discussed.

Probabilistic tools for planning and operating power systems with distributed energy storage
Probabilistic tools for planning and operating power systems with distributed energy storage

Stochastic energy flows are an increasingly important phenomenon in today's power system planning and operation. They are – among other reasons – caused by large amounts of stochastic generation such as wind. The inclusion of energy storage devices, distributed in future systems (distributed energy storage – DES), is continuously being mentioned as a possibility to alleviate some of the problems arising from stochastic generation. The authors show that the potential ownership of the DES systems is an important criterion on which probabilistic methods will be applied for assessment. The potential owners are either the grid operators, the generation owners, or the energy traders. For the grid operators being the DES owners, storage operation will have to be integrated into the planning of the system, therefore multivariate nonparametric time series analysis and synthesis methods have to be applied to recorded data of stochastic energy resources. Together with suited storage models, the implications of DES on the planning of the system can then be assessed. For the producers or traders being the owners of the DES, the topic to be addressed is the real-time operation of each storage device in the power system, which is linked to the optimization of the economic value of the stochastic resources. In this case, forecasting and operations research issues are paramount. Recently developed methods including scenario development from non-parametric forecast models for the following trading period and probabilistic assessment of necessary storage capacities for hedging with given financial risks are explained. It is generally stated that the non-standard distributions of the stochastic infeeds, as well as complex chronological persistence and interdependence phenomena complicate the modelling procedure and leave space for a large range of research activities on DES in the future. The exact description of how the owners of storage assets are embedded into the energy market frameworks of the future is crucial for the probabilistic quantification of benefits introduced by DES.
Spatio-temporal modeling of wind power prediction errors

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Vlasova, J., Kotwa, E., Nielsen, H. A. O. T. 3., Madsen, H., Pinson, P.
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference 2008
Source: orbit
Source ID: 223278
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2008 – Research

The effects of wind power forecasts on electricity spot prices in Denmark

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Jonsson, T., Madsen, H., Pinson, P.
Publication date: 2008

Host publication information
Title of host publication: Proceedings of the European Wind Energy Conference 2008
Source: orbit
Source ID: 223280
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2008 – Research

Virtual laboratories for short-term forecasting and other benchmarks of the POW

General information
Publication status: Published
Organisations: Meteorology, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Giebel, G., Pinson, P., Perez, I., Lozano, S., Kariniotakis, G., Von Bremen, L., Sood, A.
Publication date: 2008

Host publication information
Title of host publication: Conference proceedings (online)
Publisher: European Wind Energy Association (EWEA)
Source: orbit
Source ID: 232715
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2008 – Research

Adaptive Markov-switching modelling for offshore wind power fluctuations

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Integration & Planning, Department of Wind Energy
Contributors: Pinson, P., Madsen, H., Sørensen, P. E., Cutululis, N. A.
Ensemble predictions: Understanding uncertainties

General information
Publication status: Published
Organisations: Risø National Laboratory for Sustainable Energy, Meteorology, Wind Energy Division, Mathematical Statistics, Department of Informatics and Mathematical Modeling, Danish Meteorological Institute
Publication date: 2007

Evaluation of Nonparametric Probabilistic Forecasts of Wind Power
Predictions of wind power production for horizons up to 48-72 hour ahead comprise a highly valuable input to the methods for the daily management or trading of wind generation. Today, users of wind power predictions are not only provided with point predictions, which are estimates of the most likely outcome for each look-ahead time, but also with uncertainty estimates given by probabilistic forecasts. In order to avoid assumptions on the shape of predictive distributions, these probabilistic predictions are produced from nonparametric methods, and then take the form of a single or a set of quantile forecasts. The required and desirable properties of such probabilistic forecasts are defined and a framework for their evaluation is proposed. This framework is applied for evaluating the quality of two statistical methods producing full predictive distributions from point predictions of wind power. These distributions are defined by 18 quantile forecasts with nominal proportions spanning the unit interval. The relevance and interest of the introduced evaluation framework are consequently discussed.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Møller, J. K., Nielsen, H. A. O. 3., Madsen, H., Kariniotakis, G. N.
Publication date: 2007

Fluctuations of offshore wind generation: Statistical modelling
The magnitude of power fluctuations at large offshore wind farms has a significant impact on the control and management strategies of their power output. If focusing on the minute scale, one observes successive periods with smaller and larger
power fluctuations. It seems that different regimes yield different behaviours of the wind power output. This paper concentrates on the statistical modelling of offshore power fluctuations, with particular emphasis on regime-switching models. More precisely, Self-Exciting Threshold AutoRegressive (SETAR), Smooth Transition AutoRegressive (STAR) and Markov-Switching AutoRegressive (MSAR) models are considered. The particularities of these models are presented, as well as methods for the estimation of their parameters. Simulation results are given for the case of the Horns Rev and Nysted offshore wind farms in Denmark, for time-series of power production averaged at a 1, 5, and 10-minute rate. The exercise consists in one-step ahead forecasting of these time-series with the various regime-switching models. It is shown that the MSAR model, for which the succession of regimes is represented by a hidden Markov chain, significantly outperforms the other models, for which the rules for the regime-switching are explicitly formulated.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Wind Energy Systems, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Department of Buildings and Energy
Contributors: Pinson, P., Christensen, L. E., Madsen, H., Sørensen, P. E., Donovan, M. H., Jensen, L. E.
Publication date: 2007

Host publication information
Title of host publication: EWEC 2007, 'European Wind Energy Conference', Scientific Track, Milan, Italy
Source: orbit
Source ID: 200321
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2007 › Research › peer-review

Generation of statistical scenarios of short-term wind power production
Short-term (up to 2-3 days ahead) probabilistic forecasts of wind power provide forecast users with a paramount information on the uncertainty of expected wind generation. Whatever the type of these probabilistic forecasts, they are produced on a per horizon basis, and hence do not inform on the development of the forecast uncertainty through forecast series. This issue is addressed here by describing a method that permits to generate statistical scenarios of wind generation that accounts for the interdependence structure of prediction errors, in plus of respecting predictive distributions of wind generation. The approach is evaluated on the test case of a multi-MW wind farm over a period of more than two years. Its interest for a large range of applications is discussed.

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Papaefthymiou, G., Klockl, B., Nielsen, H. A.
Publication date: 2007

Host publication information
Title of host publication: IEEE PowerTech Conference 2007, Lausanne, Switzerland
Publisher: IEEE
ISBN (Print): 978-1-4244-2189-3
Electronic versions:
Pinson.pdf
DOIs: 10.1109/PCT.2007.4538366

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Source: orbit
Source ID: 200322
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2007 › Research › peer-review

HRensembleHR - High Resolution Ensemble for Horns Rev

General information
Publication status: Published
Contributors: Moehrlen, C., Jørgensen, J., Pinson, P., Madsen, H., Kristoffersen, J. R.
Publication date: 2007
Methods for the estimation of the uncertainty of wind power forecasts

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Nielsen, H. A. O. 3., Madsen, H., Lange, M., Kariniotakis, G.
Publication date: 2007

Publication information
Original language: English
Electronic versions: tr07_14.pdf
URLs: http://www2.imm.dtu.dk/pubdb/views/publication_details.php?id=5328
Source: orbit
Source ID: 201571
Research output: Book/Report › Report – Annual report year: 2007 › Research

Non-parametric probabilistic forecasts of wind power: required properties and evaluation

Predictions of wind power production for horizons up to 48-72 hour ahead comprise a highly valuable input to the methods for the daily management or trading of wind generation. Today, users of wind power predictions are not only provided with point predictions, which are estimates of the conditional expectation of future generation for each look-ahead time, but also with uncertainty estimates given by probabilistic forecasts. In order to avoid assumptions on the shape of predictive distributions, these probabilistic predictions are produced from nonparametric methods, and then take the form of a single or a set of quantile forecasts. The required and desirable properties of such probabilistic forecasts are defined and a
framework for their evaluation is proposed. This framework is applied for evaluating the quality of two statistical methods producing full predictive distributions from point predictions of wind power. These distributions are defined by a number of quantile forecasts with nominal proportions spanning the unit interval. The relevance and interest of the introduced evaluation framework are discussed.

**General information**
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Nielsen, H. A., Møller, J. K., Madsen, H., Kariniotakis, G.
Pages: 497-587
Publication date: 2007
Peer-reviewed: Yes

**Publication information**
Journal: Wind Energy
Volume: 10
Issue number: 6
ISSN (Print): 1095-4244
Ratings:
Scopus rating (2007): SJR 0.942 SNIP 1.397
Web of Science (2007): Indexed yes
Original language: English
DOI:
10.1002/we.230
URLs:
http://www2.imm.dtu.dk/pubdb/p.php?5068
Source: orbit
Source ID: 199763
Research output: Contribution to journal › Journal article – Annual report year: 2007 › Research › peer-review

**POW'WOW virtual laboratories for wind resource assessment and forecasting**

**General information**
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling, Ecole des Mines de Paris, National Renewable Energy Center
Contributors: Kariniotakis, G., Pinson, P., Lozano, S., Marti, I.
Publication date: 2007

**Host publication information**
Title of host publication: Proc. of the 2007 European Wind Energy Conference
Source: orbit
Source ID: 209989
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2007 › Research

**Robust estimation of time-varying coefficient functions - Application to the modeling of wind power production**

**General information**
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Pinson, P., Nielsen, H. A., Madsen, H.
Publication date: 2007

**Publication information**
Publisher: Informatics and Mathematical Modelling, Technical University of Denmark, DTU
Original language: English
Source: orbit
Source ID: 201017
Research output: Book/Report › Report – Annual report year: 2007 › Research › peer-review

**Skill forecasting from different wind power ensemble prediction methods**
Trading wind generation from short-term probabilistic forecasts of wind power

Due to the fluctuating nature of the wind resource, a wind power producer participating in a liberalized electricity market is subject to penalties related to regulation costs. Accurate forecasts of wind generation are therefore paramount for...
reducing such penalties and thus maximizing revenue. Despite the fact that increasing accuracy in spot forecasts may
reduce penalties, this paper shows that, if such forecasts are accompanied with information on their uncertainty, i.e., in the
form of predictive distributions, then this can be the basis for defining advanced strategies for market participation. Such
strategies permit to further increase revenues and thus enhance competitiveness of wind generation compared to other
forms of dispatchable generation. This paper formulates a general methodology for deriving optimal bidding strategies
based on probabilistic forecasts of wind generation, as well as on modeling of the sensitivity a wind power producer may
have to regulation costs. The benefits resulting from the application of these strategies are clearly demonstrated on the
test case of the participation of a multi-MW wind farm in the Dutch electricity market over a year.
On the quality and value of probabilistic forecasts of wind generation

While most of the current forecasting methods provide single estimates of future wind generation, some methods now allow one to have probabilistic predictions of wind power. They are often given in the form of prediction intervals or quantile forecasts. Such forecasts, since they include the uncertainty information, can be seen as optimal for the management or trading of wind generation. This paper explores the differences and relations between the quality (i.e., statistical performance) and the operational value of these forecasts. An application is presented on the use of probabilistic predictions for bidding in a European electricity market. The benefits of a probabilistic view of wind power forecasting are clearly demonstrated.
Standardizing the performance evaluation of short-term wind prediction models

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Madsen, H., Pinson, P., Kariniotakis, G., Nielsen, H. A., Nielsen, T. S.
Pages: 475-489
Publication date: 2005
Peer-reviewed: No

Publication information
Journal: Wind Engineering
Volume: 29
Issue number: 6
ISSN (Print): 0309-524X
Ratings:
Scopus rating (2005): SJR 0.255 SNIP 0.698
Web of Science (2005): Indexed yes
Original language: English
URLs:
http://www2.imm.dtu.dk/pubdb/p.php?4262
Source: orbit
Source ID: 191417
Research output: Contribution to journal › Journal article – Annual report year: 2005 › Research

A protocol for standardizing the performance evaluation of short-term wind power prediction models

General information
Publication status: Published
Organisations: Mathematical Statistics, Department of Informatics and Mathematical Modeling
Contributors: Madsen, H., Kariniotakis, G., Nielsen, H. A., Nielsen, T. S., Pinson, P.
Publication date: 2004

Host publication information
Title of host publication: Proceedings of the 2004 Global Windpower Conference and Exhibition
URLs:
http://www.awea.org
Source: orbit
Source ID: 154636
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2004 › Research › peer-review

Projects:

Peer-to-peer Markets for Heat and Electricity
Frölke, L., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Sousa, T., Supervisor
01/09/2019 → 31/08/2022
Project: PhD

Data-driven Optimization of Distribution Grids
Murzakanov, I., PhD Student, Department of Electrical Engineering
Chatzivasileiadis, S., Main Supervisor
Pinson, P., Main Supervisor
01/09/2019 → 31/08/2022
Market Design for Future Highly Interconnected Multi-Carrier Energy Systems
Ratha, A., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Kazempour, J., Supervisor
Virag, A., Supervisor
01/12/2018 → 30/11/2021

Optimization and Market Integration of Multi-Area AC/HVDC Grids under Uncertainty
Tosatto, A., PhD Student, Department of Electrical Engineering
Chatzivasileiadis, S., Main Supervisor
Pinson, P., Supervisor
Weckesser, J. T. G., Supervisor
Forskningsrådsfinansiering
01/02/2018 → 31/01/2021

Efficient and Scalable Market Design for Renewable-based Integrated Energy Systems
Schwele, A., PhD Student, Department of Electrical Engineering
Kazempour, J., Main Supervisor
Pinson, P., Supervisor
Forskningsrådsfinansiering
01/09/2017 → 31/08/2020

Advanced Game-Theoretical Aspects in Electricity Markets
Dvorkin, V., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Kazempour, J., Supervisor
Technical University of Denmark
01/09/2017 → 31/08/2020

Optimization, Control, and Stability of AC-DC Grids under Uncertainty
Venzke, A., PhD Student, Department of Electrical Engineering
Chatzivasileiadis, S., Main Supervisor
Pinson, P., Supervisor
Technical University of Denmark
01/06/2017 → 31/05/2020

Market design and operations for Energy Collectives
Moret, F., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Papakonstantinou, A., Supervisor
Offentlig finansiering
01/05/2017 → 30/04/2020

Predicting and mobilizing energy flexibility in intelligent buildings
Christensen, M. H., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Rønsberg, S., Supervisor
Industrial PhD  
01/11/2016 → 30/06/2020  
Award relations: Predicting and mobilizing energy flexibility in intelligent buildings  
Project: PhD

Optimal Voltage Control of Distribution Networks with High Penetration of Distributed Energy Resources (DERs)  
Hermann, A. N. A., PhD Student, Department of Electrical Engineering  
Østergaard, J., Main Supervisor  
Huang, S., Supervisor  
Kazempour, J., Supervisor  
Pinson, P., Examiner  
Capitanescu, F., Examiner  
Weber, C., Examiner  
Samfinansieret - Andet  
01/09/2014 → 12/06/2019  
Award relations: Optimal Voltage Control of Distribution Networks with High Penetration of Distributed Energy Resources (DERs)  
Project: PhD

Market Mechanisms for Integrated Energy Systems  
Mitridati, L. M. M., PhD Student, Department of Electrical Engineering  
Pinson, P., Main Supervisor  
Kazempour, J., Supervisor  
Chatzivasileiadis, S., Examiner  
Kamgarpour, M., Examiner  
Low, S. H., Examiner  
Samfinansieret - Andet  
01/11/2015 → 12/06/2019  
Award relations: Market Mechanisms for Integrated Energy Systems  
Project: PhD

Smart end user data analysis and pattern recognition  
Le Ray, G., PhD Student, Department of Electrical Engineering  
Pinson, P., Main Supervisor  
Bindner, H. W., Examiner  
Bessa, R. J. G. S. B., Examiner  
Goude, Y., Examiner  
Eksternt finansieret virksomhed  
01/12/2015 → 14/08/2019  
Award relations: Smart end user data analysis and pattern recognition  
Project: PhD

Market Mechanisms for Integrated Energy Systems  
Ordoudis, C., PhD Student, Department of Electrical Engineering  
Pinson, P., Main Supervisor  
Morales González, J. M., Supervisor  
Kazempour, J., Supervisor  
Chatzivasileiadis, S., Examiner  
Van Hentenryck, P., Examiner  
Siddiqui, A., Examiner  
Eksternt finansieret virksomhed  
01/07/2015 → 23/01/2019  
Award relations: Market Mechanisms for Integrated Energy Systems  
Project: PhD

Statistical modelling of space-time processes with  
Lenzi, A., PhD Student, Department of Mathematics  
Ersbøll, B. K., Main Supervisor  
Clemmensen, L. K. H., Supervisor  
Pinson, P., Supervisor  
Stockmarr, A., Examiner  
Girard, R., Examiner
Nystrup, P., PhD Student, Department of Mathematics
Madsen, H., Main Supervisor
Hansen, B. W., Supervisor
Larsen, H. O., Supervisor
Lindstrøm, K. J. E. L., Supervisor
Pinson, P., Examiner
Pedersen, L. H., Examiner
Dahlquist, M., Examiner
Industrial PhD
15/11/2014 → 13/03/2018
Award relations: Dynamic Asset Allocation: Identifying Regime Shifts in Financial Time Series to Build Robust Portfolios.
Project: PhD

A Diagnostic and Predictive Framework for Wind Turbine Drive Train Monitoring
Bach-Andersen, M., PhD Student, Department of Mathematics
Winther, O., Main Supervisor
Rømer-Odgaard, B., Supervisor
Pinson, P., Examiner
Gram-Hansen, K., Examiner
Giusti, A., Examiner
Industrial PhD
A Diagnostic and Predictive Framework for Wind Turbine Drive Train Monitoring
1/03/2014 → 15/11/2017
Award relations: A Diagnostic and Predictive Framework for Wind Turbine Drive Train Monitoring
Project: PhD

Integrated Wind Power Planning Tool
Rosgaard, M. H., PhD Student, Department of Wind Energy
Hahmann, A. N., Main Supervisor
Madsen, H., Supervisor
Pinson, P., Examiner
Nissen, J. N., Examiner
Wilson, C. G., Examiner
Ansat eksternt
01/10/2011 → 24/08/2015
Award relations: Integrated Wind Power Planning Tool
Project: PhD

Methods for enabling utilisation of the potential flexibility in power production and consumption of entities connected in the low voltage network in a Virtual Power Plants framework
Thavlov, A., PhD Student, Department of Electrical Engineering
Bindner, H. W., Main Supervisor
Hilger, K. B., Supervisor
Pinson, P., Examiner
Ferrarini, L., Examiner
Nordström, L. M., Examiner
Institut, samfinansiering
01/02/2010 → 28/09/2015
Award relations: Methods for enabling utilisation of the potential flexibility in power production and consumption of entities connected in the low voltage network in a Virtual Power Plants framework
Project: PhD

Estimation of Conditional densities for predictions in nonlinear stochastic processes - with applications to wind power systems
Tastu, J., PhD Student, Department of Informatics and Mathematical Modeling
Madsen, H., Main Supervisor
Pinson, P., Supervisor  
Poulsen, N. K., Examiner  
Lindström, E., Examiner  
Kariniotakis, G., Examiner  
DTU stipendium  
01/08/2007 → 12/12/2013  
Award relations: Estimation of Conditional densities for predictions in nonlinear stochastic processes - with applications to wind power systems  
Project: PhD

**Multivariate Probabilistic Forecasting for Energy Systems**  
Iversen, J. E. B., PhD Student, Department of Mathematics  
Madsen, H., Main Supervisor  
Morales González, J. M., Supervisor  
Møller, J. K., Supervisor  
Pinson, P., Examiner  
Dent, C., Examiner  
Lindström, E., Examiner  
Technical University of Denmark  
01/10/2011 → 21/09/2015  
Award relations: Multivariate Probabilistic Forecasting for Energy Systems  
Project: PhD

**Modeling and Forecasting for Optimal Participation of Renewable Energy in Deregulated Energy Markets**  
Jónsson, T., PhD Student, Department of Informatics and Mathematical Modeling  
Pinson, P., Main Supervisor  
Nielsen, T. S., Supervisor  
Poulsen, N. K., Supervisor  
Kulahci, M., Examiner  
McSharry, P. E., Examiner  
Meibom, P., Examiner  
ErhvervsPhD-ordningen VTU  
01/11/2008 → 24/08/2012  
Award relations: Modeling and Forecasting for Optimal Participation of Renewable Energy in Deregulated Energy Markets  
Project: PhD

**Mesoscale Atmospheric Variability and the Variation of wind and Production for Off-shore Wind Farms**  
Vincent, C. L., PhD Student, Risø National Laboratory for Sustainable Energy  
Giebel, G., Main Supervisor  
Hahmann, A. N., Supervisor  
Pinson, P., Supervisor  
Badger, J., Examiner  
Barstad, I., Examiner  
Knievel, J. C., Examiner  
Centerfinansieret  
01/01/2008 → 06/04/2011  
Award relations: Mesoscale Atmospheric Variability and the Variation of wind and Production for Off-shore Wind Farms  
Project: PhD

**Impact of Stochastic Generation on Electricity Market Dynamics**  
Zugno, M., PhD Student, Department of Informatics and Mathematical Modeling  
Pinson, P., Main Supervisor  
Morales González, J. M., Supervisor  
Madsen, H., Supervisor  
Rasmussen, K. M., Examiner  
Boomsma (fhv. Kristoffersen), T. K., Examiner  
Hobbs, B. F., Examiner  
Technical University of Denmark  
01/01/2010 → 30/08/2013  
Award relations: Impact of Stochastic Generation on Electricity Market Dynamics  
Project: PhD
Exploring Market Models for a European Electricity Grid With a High Penetration of Renewable Energy Sources
Jensen, T. V., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Greiner, M. O. W., Supervisor
Wu, Q., Examiner
Bjørndal, M. H., Examiner
Papavasiliou, A., Examiner
Samfinansieret - Andet
01/09/2013 → 13/09/2017
Award relations: Exploring Market Models for a European Electricity Grid With a High Penetration of Renewable Energy Sources
Project: PhD

Control Strategies for price based control of demand side units
Sossan, F., PhD Student, Department of Electrical Engineering
Bindner, H. W., Main Supervisor
Gehrke, O., Supervisor
Nærgård, P. B., Supervisor
Pinson, P., Examiner
Andersson, G., Examiner
Anjos, M. F., Examiner
Institut, samfinansiering
01/12/2010 → 20/08/2014
Award relations: Control Strategies for price based control of demand side units
Project: PhD

Static Security Assessment and PMU Data Validation
Møller, J. G., PhD Student, Department of Electrical Engineering
Østergaard, J., Main Supervisor
Jóhannsson, H., Supervisor
Pinson, P., Examiner
Hug-Glanzman, G., Examiner
Huang, Z. H., Examiner
Samfinansierede - Virksomhed
01/08/2013 → 12/04/2017
Award relations: Static Security Assessment and PMU Data Validation
Project: PhD

System-wide socio-economic and reliability impact of active management of distribution grids and distributed energy resources
Wang, Q., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Morales González, J. M., Supervisor
Meibom, P., Supervisor
Pineda Morente, S., Supervisor
Yang, G., Examiner
Bakirtzis, A., Examiner
Bessa, R. J. G. S. B., Examiner
Technical University of Denmark
15/06/2013 → 30/09/2016
Award relations: System-wide socio-economic and reliability impact of active management of distribution grids and distributed energy resources
Project: PhD

Electricity market design for distributed energy resources and flexible demand
Larsen, E. M., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Ding, Y., Supervisor
Østergaard, J., Supervisor
Kok, K., Examiner
Gibescu, M., Examiner
Biskas, P., Examiner
Technical University of Denmark
Award relations: Electricity market design for distributed energy resources and flexible demand
Project: PhD

Market Design and Network Planning for distribution Grid
Zhang, C., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Ding, Y., Supervisor
Nielsen, A. H., Examiner
Zhang, X., Examiner
Wen, F., Examiner
Technical University of Denmark
15/11/2012 → 16/03/2016
Award relations: Market Design and Network Planning for distribution Grid
Project: PhD

On-line Dynamic Security Assessment in Power Systems
Weckesser, J. T. G., PhD Student, Department of Electrical Engineering
Østergaard, J., Main Supervisor
Johannsson, H., Supervisor
Pinson, P., Examiner
Glavic, M., Examiner
Kundur, P., Examiner
Technical University of Denmark
01/09/2011 → 07/05/2015
Award relations: On-line Dynamic Security Assessment in Power Systems
Project: PhD

Energy and Ancillary Services in Future Electricity Markets
Soares, T., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Wu, Q., Examiner
Ernst, D., Examiner
Bell, K. R. W., Examiner
Technical University of Denmark
01/02/2014 → 10/05/2017
Award relations: Energy and Ancillary Services in Future Electricity Markets
Project: PhD

NonLinear modelling for energy systems
Trombe, P., PhD Student, Department of Informatics and Mathematical Modeling
Madsen, H., Main Supervisor
Pinson, P., Supervisor
Larsen, R. W., Examiner
Greiner, M. O. W., Examiner
Thorarinsson, T. L., Examiner
Technical University of Denmark
01/01/2009 → 22/03/2013
Award relations: NonLinear modelling for energy systems
Project: PhD

Modelling Of Market-Based Cross-Border Exchange Of Balancing Power
Delikaraoglou, S., PhD Student, Department of Electrical Engineering
Pinson, P., Main Supervisor
Morales Gonzalez, J. M., Supervisor
Heussen, K., Supervisor
Rapke, S., Examiner
Tomasgard, A., Examiner
Kirschen, D., Examiner
Technical University of Denmark
01/05/2013 → 07/12/2016
Award relations: Modelling Of Market-Based Cross-Border Exchange Of Balancing Power
Best Paths

To establish a low-carbon economy and to keep the global average temperature rise below 2°C, industrialised countries have to reduce greenhouse gas emission by up to 95% by 2050. Europe’s energy sector is expected to make a major contribution towards achieving these reductions and to become the engine for a low-carbon economy.

The integration of decentralised renewable energy systems into the power grid is one of the principal drivers for investments in electricity infrastructure and offers many opportunities for the reduction of grid loads and energy losses in transportation. At the same time, grid operators and the electricity industry are facing major challenges in implementing this complete transformation of the way electricity is generated and transmitted.

By 2050, the majority of Europe’s electricity will come from renewables and the continent’s transmission grids will need to be geared to both transporting large quantities of offshore wind-generated electricity and integrating it into micro-grids. For electricity production, onshore and offshore wind power is a key provider, which is projected to increase to over 190 GW of installed capacity in the EU by 2020.

The challenge of integrating large volumes of renewable energies into the grid hinges on their intermittent nature and uneven geographical distribution. Major development of the European grid infrastructure is thus considered critical to maintaining reliable power supplies and bringing renewable-generated electricity from generation sites to far away consumption sites.

Pinson, P., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Thams, F., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Electric Power Systems
Halilbasic, L., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Chatzivasileiadis, S., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets

01/10/2014 → 30/09/2018
Keywords: Renewable Energy, HVDC, Electricity Markets, Energy System Modelling

Market Mechanisms for Integrated Energy Systems

Ordoudis, C., PhD Student, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Pinson, P., Main Supervisor, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Morales González, J. M., Supervisor, Department of Applied Mathematics and Computer Science, Dynamical Systems
Power Fluctuations from Large Offshore Wind Farms
The project has developed and verified simulation and prediction models for power fluctuations in large wind farms. The verification is based on extensive measurements in the two large offshore wind farms in Denmark: Horns Rev and Nysted. The models can also be applied to simulation of wind power fluctuations from wind turbines distributed over a larger area than a wind farm. The advantage of the prediction models is that they can be applied in the operation, but these models require a training period before they work in a new system. On the other hand, the simulation model can simulate power fluctuations with possible future wind power developments, based on information about size and location of the individual wind turbines. Thus, the simulation model is a planning tool.
Sørensen, P. E., Project Manager, Department of Wind Energy, Wind Energy Systems, Risø National Laboratory for Sustainable Energy
Cutululis, N. A., Project Participant, Department of Wind Energy, Wind Energy Systems, Risø National Laboratory for Sustainable Energy
Madsen, H., Project Participant, Department of Applied Mathematics and Computer Science
Pinson, P., Project Participant, Department of Applied Mathematics and Computer Science
01/10/2004 → 30/09/2008
Collaborators: Ørsted A/S, Vattenfall Vindkraft A/S
Project: Research

EcoGrid EU: EcoGrid EU - Large scale Smart Grids demonstration of real time market-based integration of DER and DR
The EcoGrid EU project proposal offers Europe a "fast track" evolution towards Smart Grid dissemination and deployment in the distributed electricity grid. The aim is to contribute to the European 20-20-20 goals by showing that it is possible to operate a distribution power system (on the Danish island of Bornholm) with more than 50% renewable energy sources (RES) making active use of new communication technology and innovative market solutions. The EcoGrid EU concept will contribute to the operation of the transmission system by offering the TSOs additional balancing and ancillary services. EcoGrid EU is a large-scale demonstration of a complete power system including the following key elements:
- The total distributed grid with all resources up to 60 kV, 28,000 customers, 55 MW peak load, 268 GWh electricity consumption and 500 GWh heat demand
- All distributed RES including wind power, photo voltaic, biomass, biogas, five units with heat accumulation tanks for
district heating and electric vehicles (EVs)
- ICT systems and a new information architecture allowing all units of distributed energy resources (RES) and demand response (DR) to participate in the power market. There will be a communication and information system and new operational procedures
- Full market participation utilizing all parts of the existing power market and developing a new near real-time market for deliverance of ancillary services both from RES and DR
- "Smart" Meters, "Smart" Controllers and E-mobility by using electric vehicles as an integrated part of the total concept
- Storage of energy will be demonstrated using heat appliances as well as batteries of the electric vehicles

The EcoGrid EU-project will combine knowledge from previous EU funded projects into a large-scale demonstration where the outcome is substantial contribution to a “Road map for European Smart Grids deployment”.

Pedersen, A. B., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Ding, Y., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Feng, D., Project Participant, Department of Electrical Engineering
Larsen, E. M., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Nielsen, A. H., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Pedersen, R. R., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Pensini, A., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Pineda Morente, S., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Hashemi Toghroljerdi, S., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Wu, Q., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Yang, G., Project Participant, Department of Electrical Engineering, Electric Energy Systems
Østergaard, J., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy
Pinson, P., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Le Ray, G., Project Participant, Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets

EU FP7: DKK178,725,000.00
01/04/2011 → 30/09/2015

Award relations: EcoGrid EU - Large scale Smart Grids demonstration of real time market-based integration of DER and DR

Documents:
Fact sheet EcoGrid EU 2015
Project: Research

Activities:

Integrated bidding and operating strategies for wind farm-energy storage systems
Period: 2015
Pierre Pinson (Invited speaker)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets

Related event
European conference for Operational Research 2015
12/07/2015 → 15/07/2015
Glasgow, United Kingdom
Activity: Talks and presentations › Conference presentations

Modelling of high-dimensional space-time dynamics of renewables
Period: 2015
Pierre Pinson (Invited speaker)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets

Description
**Invited seminar, Universite Paris 7, France**

**Related external organisation**

**Unknown Organization**
Activity: Talks and presentations › Conference presentations

**Renewable energy forecasting**
Period: 2015
Pierre Pinson (Lecturer)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets

**Related event**

**EuroTech Winter School: Smart Energy**
02/02/2015 → 15/02/2015
Lausanne, Switzerland
Activity: Talks and presentations › Conference presentations

**Towards future electricity markets with large penetration of renewable generation**
Period: 2015
Pierre Pinson (Invited speaker)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets

**Description**
Invited seminar, ETH Zurich, Switzerland

**Related external organisation**

**Unknown Organization**
Activity: Talks and presentations › Conference presentations

**Towards the usage of new large datasets for renewable energy applications**
Period: 2015
Pierre Pinson (Lecturer)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets

**Description**
Invited Seminar, University of Bonn, Germany

**Related external organisation**

**Unknown Organization**
Activity: Talks and presentations › Conference presentations

**Global Energy Forecasting Competition 2014**
Period: 2014 → …
Pierre Pinson (Participant)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets
Department of Applied Mathematics and Computer Science

**Description**
Global Energy Forecasting Competition 2014: GEFCom2014

**Related event**

Global Energy Forecasting Competition 2014
15/08/2015 → 15/12/2015
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

**International Journal of Forecasting (Journal)**
Period: 2014 → …
Pierre Pinson (Editor)
Department of Electrical Engineering
Center for Electric Power and Energy
Energy Analytics and Markets
Department of Applied Mathematics and Computer Science

**Related journal**

International Journal of Forecasting
0169-2070
ISI indexed (2013): ISI indexed yes
Central database
Activity: Editorial work and peer review › Journal editor › Research

**Discrimination ability of the Energy score(s)**
Period: 2013
Pierre Pinson (Lecturer)
Department of Electrical Engineering
Center for Electric Power and Energy
Department of Applied Mathematics and Computer Science

**Description**
Invited seminar at University of Heidelberg, Institute of Applied Mathematics, workshop on "Evaluation of multivariate probabilistic forecasts"

**Related external organisation**

Unknown Organization
Activity: Talks and presentations › Conference presentations

**Prevoir l'électricité produite par nos énergies renouvelables**
Period: 2013
Pierre Pinson (Participant)
Department of Applied Mathematics and Computer Science
Department of Electrical Engineering
Center for Electric Power and Energy

**Description**
Broad-audience short letter (in French), for the French edition of Mathematics for Planet Earth (Mathematiques de la planete Terre), "Un jour, une breve", online at mpt2013.fr
**Rendre la consommation d'électricité plus flexible et controlable**

**Period:** 2013  
**Pierre Pinson** (Participant)

Department of Electrical Engineering  
Center for Electric Power and Energy  
Department of Applied Mathematics and Computer Science

**Description**

Broad-audience short letter (in French), for the French edition of Mathematics for Planet Earth (Mathematiques de la planete Terre), "Un jour, une breve", online at mpt2013.fr

**Renewable energy forecasts ought to be probabilistic!**

**Period:** 2013  
**Pierre Pinson** (Lecturer)

Department of Applied Mathematics and Computer Science  
Department of Electrical Engineering  
Center for Electric Power and Energy

**Description**

Invited lecture at "WIPFOR - Forecasting for the energy industry", Paris, France

**Renewables in electricity markets: Stochastic modelling and optimization**

**Period:** 2013  
**Pierre Pinson** (Lecturer)

Department of Applied Mathematics and Computer Science  
Department of Electrical Engineering  
Center for Electric Power and Energy

**Description**

Invited seminar at Wroclaw University of Technology, Poland

**Stochastic power generation from renewables: forecasting and optimization challenges for its optimal integration.**

**Period:** 2013  
**Pierre Pinson** (Lecturer)

Department of Applied Mathematics and Computer Science  
Department of Electrical Engineering  
Center for Electric Power and Energy

**Description**

Invited lecture at "Energy Systems Week", Isaac Newton Institute, University of Cambridge, UK
The value of probabilistic information for energy applications - from theory to reality.
Period: 2013
Pierre Pinson (Lecturer)
Department of Electrical Engineering
Center for Electric Power and Energy
Department of Applied Mathematics and Computer Science
Description
Invited lecture at the German Weather Service (DWD)

Web-based wind power forecasting competition 2012 - Wind Forecasting
Period: 2012
Pierre Pinson (Organizer)
Department of Applied Mathematics and Computer Science
Department of Electrical Engineering
Center for Electric Power and Energy
Description
Global Energy Forecasting competition
Web-based wind power forecasting competition hosted by Kaggle.com (150 participants worldwide)

I E E E Transactions on Power Systems (Journal)
Period: 2011 → …
Pierre Pinson (Editor)
Department of Electrical Engineering
Center for Electric Power and Energy
Department of Applied Mathematics and Computer Science

Wind Energy (Journal)
Period: 2010 → …
Pierre Pinson (Editor)
Department of Electrical Engineering
Center for Electric Power and Energy
Department of Applied Mathematics and Computer Science

Related journal

Wind Energy
1095-4244

Central database
Activity: Editorial work and peer review › Journal editor › Research

Prizes:

IDA Elektropris
Pierre Pinson (Recipient)
Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets

Details
Awarded date: 2018
Granting Organisations: The Danish Society of Engineers, IDA
Prize: Prizes, scholarships, distinctions

Second best student paper award (Basil Papadias Award) at IEEE PowerTech 2019 Conference
Anna Schwele (Recipient), Christos Ordoudis (Recipient), Jalal Kazempour (Recipient) & Pierre Pinson (Recipient)
Center for Electric Power and Energy, Energy Analytics and Markets, Department of Electrical Engineering

Description
For paper:

Details
Awarded date: 26 Jun 2019
Degree of recognition: International
event: 13th IEEE PowerTech 2019
Prize: Prizes, scholarships, distinctions

Press clippings:

Spotlight on Denmark
Pierre Pinson
01/01/2015
Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets

Media contribution (1)

Spotlight on Denmark
01/01/2015
Nature jobs, Print
Pierre Pinson
Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Press/Media: Press / Media

La France sans nucleaire, c'est possible!
Pierre Pinson
01/01/2015
Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
La France sans nucléaire, c’est possible!
01/01/2015
Science et Vie, Print
Pierre Pinson
Department of Electrical Engineering, Center for Electric Power and Energy, Energy Analytics and Markets
Press/Media: Press / Media