Technical University of Denmark
Department of Electrical Engineering
Centre for Electric Power and Energy
Energy Analytics & Markets group

Overview of available projects:

1. Electricity and Gas Market Interdependencies
2. Hydro Modeling for Large-scale Energy Market Models
3. Storage for Loss Reduction in Distribution Networks
4. Strategic Ramp Offering of a Flexible Producer in the Electricity Market
5. Optimal Strategy for a Virtual Trader in a Wind-integrated Electricity Market
6. Nodal Reliability Evaluation for Distribution Network
7. Comparison of Scenario Reduction Techniques for the Stochastic Unit Commitment Problem
8. Offering Strategy of a Price-Maker Storage Unit
9. Trading Strategy of a Wind Power Producer in both Futures and Day-ahead Markets
10. Development of an Open-source Platform for Wind and Solar Probabilistic Forecasting
11. Revenue Adequacy and the Missing Money Problem in Highly Renewable Electricity Systems
12. Distributed Learning in Renewable Energy Forecasting

NOTA: Other projects can be tailored to the students' specific skills and interests!

More information on the various activities in the group can be found on the DTU CEE youTube Channel: https://www.youtube.com/playlist?list=PLwKjKt8EU3S2w2T7duSMNCxaRymIMj07Z

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Electricity and Gas Market Interdependencies

Supervisors: Pierre Pinson, Christos Ordoudis
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Over the last years, high shares of renewables are integrated in the energy systems resulting in a number of challenges in power system operations. Power generation from renewable energy sources such as wind and solar power is intermittent and hard to predict. In parallel, a significant increase has been noticed in the natural gas share of the generation mix. The share in the EU has almost tripled from 8% in 1990 to 23% in 2010. Gas-fired power plants (GFPPs) are more favorable in future power systems for a variety of reasons. Firstly, GFPPs operate with higher efficiencies than conventional thermal power plants and are more environmental friendly in terms of emissions. Additionally, technical specifications of these units, such as ramp rates and minimum start-up/shut-down times, give them a prominent role in future power systems with high share of renewables.

The increased power generation from GFPPs creates strong links between the electric power and natural gas systems. GFPPs constitute a significant fraction of the natural gas demand, which affects the total gas consumption and the flows in the natural gas network. In addition, the companies owning these power plants may need to operate in both electricity and gas markets. In principle, GFPPs need to purchase gas through long- or medium-term contracts or in the gas spot market and participate in the electricity market as producers. Gas market prices and the type of contracts may affect the economic dispatch of the units in the electricity market. For this reason, a combined operation of the two markets is important, as synergies exist and potential improvements need to be examined. Moreover, different temporal decisions have to be coordinated in terms of long-term decisions (e.g., gas contracts) and short-term decisions (e.g., scheduling in the electricity markets).

Objectives
In that context, the main objective of this MSc project is to investigate synergies and ways of aligning the electricity and gas markets in the scope of accomplishing an improved operation of the system.

Methodology
From the methodological point of view, the interdependency of electricity and gas markets can be formulated as an optimization problem by including the constraints that compose the gas and electricity market models aiming at minimizing the total cost of operating the system. Additionally, the link between the two markets via the GFPPs will be included in the model. Given time availability, renewable energy production uncertainty may be introduced in the model to examine how the scheduling of the units will be affected. The optimization models may be implemented in GAMS, Python or Matlab depending on the background of the student.

Expected results
The expected outcome includes relevant literature review, the formulation of the optimization problems and their implementations as well as their evaluation against a benchmark of a completely uncoordinated model describing the two markets.

Prerequisites
Power systems operations, energy system modeling, energy markets, basics of optimization

Hydro Modeling for Large-scale Energy Market Models

Supervisors: Pierre Pinson, Tue V. Jensen
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Renewable energy is set to cover 40% of the European electricity demand by 2030. A large share of this will be covered by solar and wind power, but for periods when the production from these sources don't meet demand, backup generation is still needed. In the European scenario, hydro plays a crucial role to ensure the energy sector is able to meet demand. In order to understand the interplay of hydro resources with the remainder of the energy system, the hydro producer must be modeled in an integrated market context. A hydro plant is constrained in how it can produce by the inflow into and the size of its reservoir. Its operation thus needs to consider the opportunity cost of discharging water now as opposed to at a later time, and reflect this opportunity cost in the bids made into the electricity market.

Traditionally, modeling of hydro plants' bidding behavior has been done from the perspective of the plant operator, with the plant seeking to produce bids which maximize the plant's profits under uncertain inflows. The models produced in this way are typically highly intricate, with a high computational complexity to model the bidding of a single plant, especially when interaction between competing firms and strategic bidding of generator portfolios are involved. As real-world electricity systems typically contain many hundreds of hydro plants, modeling large-scale systems with these models quickly become unfeasibly complex.

If hydro is to be modeled in large-scale system models, the conditions for their strategic behavior need to be written into the model directly, in a way that preserves the essential features of the strategic models without the computational overhead that traditional models entail.

Objectives
Given this challenge, this master project seeks to develop and evaluate new models for the strategic behavior of hydro plants which can be applied to large-scale system models.

Methodology
Modern market simulations are written as optimization models, solving for the least-cost dispatch of all generators in the system. The strategic bidding of a hydro generator in such a system may be written as a bilevel optimization model, with the upper level maximizing the profit of the hydro generator, and the lower level clearing the market under the hydro generator's bidding price. Models must be formulated that appropriately incorporate the limitations on hydro production but avoid the need for complex bilevel problem formulations. These models will subsequently be implemented in e.g. Python, GAMS or Matlab depending on the preference of the candidate, and compared against the bilevel formulation on small-scale test systems. Time permitting, the impact of the formulations on results from a large-scale model of the European transmission grid will be assessed.

Expected results
The expected results include a literature review on strategic hydro modeling, the formulation of several optimization problems representing the essential features of hydro production, and their implementation. The resulting models are then compared to a benchmark of a traditional hydro model.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization. The candidate would ideally have familiarity with mixed-integer modeling and/or hydro plant operation.

Storage for Loss Reduction in Distribution Networks

Supervisors: Pierre Pinson, Chunyu Zhang
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Environmental consciousness and sustainable development based on diversification of energy sources are key issues for our modern society. This leads to the fast spread of distributed energy resources (abbr. DGs) to be installed in the distribution network. This is while the high-efficiency small size generations also cause unpredictable impacts to the power systems, since their output is weather-dependent and thus intermittent. In recent years, storage units (SUs) have been widely discussed in the literature and projects to show the benefits on peak load shaving and shifting, black start initializing, and contingency smoothing are ongoing. Storage units include centralized bulk storage, residential storage, and distributed storage, such as pump storage, electric vehicles, etc.. Considering the new architecture with various distributed generation units, the distribution system is transferring to be an active management fashion, which requires a novel approach for assessing the power loss issue. Power loss occurs when power flow carried on the network, especially higher in the distribution network with large resistance and impedance. In addition, the network operator also has an economic incentive to reduce losses in their networks for maximizing its profit. However, the SU's impact characteristics for power loss issue are rarely investigated.

Since the stochastic DGs may even recast the distribution network into a bidirectional power flow, the power loss assessment becomes more complex than before. Traditionally, most studies concentrate on a specific case or develop a methodology to assess specific losses situation when a particular scenario of DG penetration has been counted. This weakens the expected evolution of losses in distribution feeders. To well address the power loss issue, the various DGs' capacities, connection points, and numbers should be concerned in a stochastic formulation. On basis of this, the SU-originated loss reduction index can be defined, and further embodied in the optimal power flow (OPF) analysis. The result of this optimization problem can be a key factor for distribution network operating and planning.

Objectives
Propose an OPF-based loss reduction assessment approach by applying the SUs with stochastic DGs in a distribution network.

Methodology
The analysis of the impacts about heterogeneous DGs on distribution losses should be carried out first, which covers the differing scenarios of DGs' number, capacity and allocation. The power losses of the distribution feeders can be assessed by a daily, monthly or yearly basis. The typical DG technologies, e.g., wind turbine (WT), photovoltaic (PV) and combined heat & power (CHP) generation are necessary to be taken into account. The stochastic programming is preferable to indicate the various DG outputs. Besides, the SU's model can be illustrated in a general expression referring to the literature. A scenario-based loss reduction index needs to be proposed accounting for the SU penetration level regarding a certain integration point. Furthermore, after modeling the individual DGs and SU, the loss reduction index can be embedded in an OPF formulation with the objective of the operation cost minimization. The new proposed index and the presented methodology should be implemented on an IEEE test system to verify their effectiveness.

Expected results
Literature review, DG and SU description, power loss index, OPF model implementation, and case studies.

Prerequisites
Power system analysis, operation, planning, stochastic programming, optimization, GAMS, MATLAB, C++.

Strategic Ramp Offering of a Flexible Producer in the Electricity Market

Supervisors:	Pierre Pinson, Jalal Kazempour
Group:	Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Over the last decade, the share of non-dispatchable renewable sources especially wind power has rapidly grown. For example, Danish wind turbines supplied 39.1% of load in average in 2014, while this figure was 33.2% in 2013. However, the inherent variability of wind power exposes the electricity markets, and inevitably the producers, to a new source of uncertainty. As an example of such variability, the electricity coming from Spanish wind turbines dropped from 8 GW at 10pm of February 18th, 2012, to 2 GW at the same hour of the subsequent day. This drop is almost equivalent to full production of six Spanish nuclear power plants. This non-dispatchable production variability faces the electricity markets to a new phenomenon, which is really challenging. One potential solution to cope with wind variability is to increase the system flexibility through adding conventional flexible producers (e.g., gas-fired generating units), demand-side flexibility resources (e.g., demand response programs), and etc. The former is the focus of this proposal.

On the other hand, the real-world electricity markets are mostly imperfect in terms of competition, i.e., some producers, so-called strategic producers, are able to alter the market clearing outcomes to their own benefits. In other words, each strategic producer maximizes its profit through making strategic offering decisions including its i) price, ii) quantity, and iii) ramp offers. Note that the market is cleared based on bids and offers submitted by all consumers and all producers, respectively. In an electricity market with significant share of wind power, a conventional flexible producer (e.g., a gas-fired unit) as a flexible generation-side resource can take the advantages of wind variability to make a business based on its ramp capability, which allows that unit to quickly change its production level (either up or down). Accordingly, this flexible producer can strategically offer its ramp capability to the market as well as its strategic price and quantity offers. These three offers may alter the market clearing procedure, so that the flexible producer's profit is maximized.

Objectives
This proposal looks to the electricity markets from a conventional flexible producer's point of view, and its aim is to develop a mathematical tool that assists that producer to maximize its expected profit through making informed offering decisions. The main contribution of this proposal is to derive the most beneficial ramp offers for the flexible producer, which has not been maturely addressed in the technical literature.

Methodology
A hierarchical (bi-level) optimization model is able to represent the offering behavior of the strategic flexible producer that maximizes its expected profit subject to market clearing conditions under wind production uncertainty. This model consists of an upper-level problem and a set of lower-level problems. Replacing each lower-level problem with its equivalent optimality conditions renders a mathematical program with equilibrium constraints (MPEC) that can be recast as a computationally tractable mixed-integer linear programming (MILP) problem. The resulting MILP problem may be solved in GAMS, Python or Matlab depending upon the background of the successful candidate.

Expected results
The expected results include relevant literature review, the formulation of the optimization problems and their implementations as well as their evaluation against a benchmark of a completely competitive flexible producer, and an inflexible producer.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization

Optimal Strategy for a Virtual Trader in a Wind-integrated Electricity Market

Supervisors: Pierre Pinson, Jalal Kazempour
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context

Over the last decade, the share of non-dispatchable renewable sources especially wind power has rapidly grown. For example, Danish wind turbines supplied 39.1% of load in average in 2014, while this figure was 33.2% in 2013. However, the inherent variability of wind power exposes the electricity markets, and inevitably the producers, to a new source of uncertainty. As an example of such a variability, the electricity coming from Spanish wind turbines dropped from 8 GW at 10 pm of February 18th, 2012, to 2 GW at the same hour of the subsequent day. This drop is almost equivalent to full production of six Spanish nuclear power plants. Besides, the wind power production is uncertain, so that the wind power forecasting in day ahead is a challenging task. These two aspects of wind production, i.e., variability and uncertainty, make the trading decisions for all market players (especially for the wind producers) too risky.

In such a risky trading environment, a player, so-called virtual trader, is motivated to participate in the market, while it generally has no physical asset. The virtual trader signs long-term contracts, so-called power purchase agreements (PPAs) with wind producers. Accordingly, the virtual trader buys the production of wind producers at a fixed price over a long time period. This way, the wind producers do not directly enter to the market clearing process. In turn, the virtual trader, as an energy seller, participates in an electricity market (e.g., day-ahead market) or several markets (e.g., futures and day-ahead markets), while the clearing price of those markets change over the time.

In this context, the virtual trader needs to make informed decisions in terms of its PPA contracts with wind producers, and in terms of its offers to be submitted to the markets. The objective of such a trader is to maximize its expected profit, while minimizing the potential risk. This decision-making process needs an appropriate mathematical tool to be developed, which is the focus of this proposal.

Objectives

This proposal looks to the electricity markets from a virtual trader's point of view, and its aim is to develop a mathematical tool that assists that trader to maximize its expected risk-constrained profit through making informed PPA and offering decisions. This problem has not been appropriately addressed in the literature review, which makes it a potential proposal for a master candidate.

Methodology

A hierarchical (bi-level) optimization model is able to model the decision-making problem of a virtual trader that maximizes its expected risk-constrained profit subject to wind production uncertainty. This model consists of an upper-level problem and a set of lower-level problems. Replacing each lower-level problem with its equivalent optimality conditions renders a mathematical program with equilibrium constraints (MPEC) that can be recast as a computationally tractable mixed-integer linear programming (MILP) problem. The resulting MILP problem may be solved in GAMS, Python or Matlab depending upon the background of the successful candidate.

Expected results

The expected results include relevant literature review, the formulation of the optimization problems and their implementation.

Prerequisites

Power systems operations, energy systems modeling, energy markets, basics of optimization

Nodal Reliability Evaluation for Distribution Network

Supervisors: Pierre Pinson, Qi Wang
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context

Currently, the high penetration of distributed energy resources (DERs) is the emerging paradigm of the distribution network. The intermittent characteristics of various DERs are difficult to be handled in the system operation process. In some extreme cases, the integration of DERs pushes the distribution network to touch the capacity limits of feeders and facilities. The major challenge is how to efficiently and effectively incorporate models for intermittent and stochastic DERs into the reliability evaluation.

From a risk management perspective, reliability evaluation plays a vital role to keep the distribution network operating in an abundant and secure environment. Vast investigations have been carried out in the literature and research projects at transmission level. However, traditional evaluation approaches may not be suitable to be directly adopted in distribution systems, where multiple contingencies have to be taken into concern to address the uncertain outcomes of the DERs.

Since the DERs are normally small size, disperse and heterogeneous. To chase the individual impacts of these DERs, the local reliability should be calculated on basis of nodal reliability evaluation approach. Combined with the transmission-level markets clearing, the impacts of DERs' reliability benefit and cost should be investigated thoroughly. Thus, the distribution network can be scheduled, expanded or reinforced accordingly.

Objectives

Propose an evaluation method to investigate the impacts of DERs regarding the nodal reliability in order to clearly the benefit and cost of the distribution system.

Methodology

In system operation process, DERs' output and demand requirements can be considered as the contingency reserve allocation. Each contingency state is constrained by the physical network limits. In a contingency state, the power delivery of the contingency reserve can be affected by the availability of the distribution feeders, DER contingency characteristics, and transmission-level market influence. On one hand, the demand could be interrupted if the market price is very high. On the other hand, the power delivery may not success considering the network constraints or DER units'/facilities' failure, which may also cause an interruption for the demand. The demand interruption cost depends on the load-shedding capacity and duration. Therefore, the contingency state should be formulated first as an optimization problem. After solving this problem, the results can conduct the normal and contingency state analysis, then, the reliability risks of demands can be evaluated by a new presented index. A IEEE RBTS test system should be carried on to identify the effectiveness of the proposed approach.

Expected results

Literature review, problem formulation, model implementation, and conclusions via RBTS-based case studies.

Prerequisites

Reliability analysis, Power system operation, optimization, GAMS or Matlab, C++.

Comparison of Scenario Reduction Techniques for the Stochastic Unit Commitment Problem

Supervisors:	Pierre Pinson, Victoria Guerrero Mestre
Group:	Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context

The aim of the unit commitment (UC) problem is to determine the combination of power plants and their corresponding generation levels in order to satisfy the demand and the reserve requirements for the entire time horizon at the minimum operating cost. Renewable energy is subject to a high variability, and the uncertainty associated with renewable energy sources makes is difficult to get an accurate forecast. With the increasing penetration of renewable generation in power systems over the last years, the way of scheduling the generation of power plants has changed. One of the currently most-used techniques for the optimization under uncertainty is the stochastic programming.

In stochastic programming, uncertainty is considered through a set of scenarios which are input data of the optimization model. Each scenario has a probability of occurrence, and the solution of the problem may has to consider a trade-off among different scenarios. In many stochastic problems, a big quantity of scenarios is needed in order to address the problem with as much information as possible. However, for such a high number of scenarios, it can be difficult of even impossible to solve the problem and obtain a numerical solution. Moreover, if a small quantity of scenarios is considered, an important amount of information may be lost. For this reason, it is important to have a comprise between the number of scenarios and the computational effort required to solve the stochastic problem. Thus, a solution for solving a stochastic problem within an acceptable computation time losing as less information as possible is to get a subset of reduced scenarios of the original scenario set that maintains a good accuracy with respect to the original set of scenarios.

Objectives

In that context, the main objective of this MSc project is to compare the expected operating cost and the computational time of the unit commitment problem considering different scenario reduction techniques.

Methodology

The first step of the proposed Master Thesis requires a literature review about the state-of-the-art of the scenario reduction techniques and their use in power management problems. Once the most relevant algorithms have been studied, their implementation may be done using Matlab, Python or GAMS, depending on the software knowledge of the student. The aforementioned algorithms will be tested in a two-stage stochastic UC problem, which may be solved using Python or GAMS.

Expected results

The expected results include a literature review about the state-of-the-art of the scenario reduction, the implementation of the most relevant scenario reduction algorithms, and a comparative analysis among the differences obtained using each of them when solving the UC optimization problem.

Prerequisites

Power systems operations, mathematical modeling, optimization, programming

Offering Strategy of a Price-Maker Storage Unit

Supervisors: Pierre Pinson, Stefanos Delikaraoglou
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
The penetration of renewable energy sources (RES) into the power system has increased significantly during the latest years. However, power generation from many RES, e.g., wind and solar power, is intermittent and partly predictable. As a result, the need for balancing capabilities is increased in order to meet the power imbalances during the actual operation of the power system.

One balancing solution that recently draws increasing attention, is the electrical energy storage (ESS) whose commercial deployment is promoted by several TSOs e.g. PJM and regulators e.g. in Germany. Storage capacities allow for inter-temporal energy arbitrage in short-term markets, i.e., storing energy during low price periods and feeding it back to the grid when the price is high. In addition, EES units can serve as a buffer for imbalances and thus minimize the deviation from the initial production schedule.

In principle, a power producer owing a storage asset would try to maximize its revenue participating in various trading floors e.g. day-ahead and balancing market. However, the optimal bidding strategy of an EES plant should take into consideration both the technical parameters of the unit as well as the expected electricity prices. Theoretically, electricity prices for day-ahead and regulating markets could be forecasted using historical data and provided as input in the optimization problem. In practice, the storage operation has an impact on price variation, especially in the balancing stage where trading volumes and market liquidity are significantly lower than those of day-ahead.

Objectives
In that context, the main objective of this MSc project is to formulate the bidding strategy of a storage unit which is a price-taker in the day-ahead market but a price-maker in the balancing market.

Methodology
From the methodological point of view, several approaches can be used to model the effect of the EES production/consumption on the balancing prices and in turn to the operational schedule and the profits of the unit.

A first approach will be to assume linearity in the supply and demand functions of the balancing market in order to model analytically the price dependency on the decisions of the EES. The problem can be formulated as a two-stage stochastic optimization model, where the first stage represents the day-ahead market decisions and the second stage represents the balancing stage offers based on scenarios of plausible system imbalances. Given time availability, more advanced methods, e.g., bi-level programing (MPEC) can be also considered in order to raise the linearity assumption of price elasticity and capture more realistically the market power of the EES. The optimization models may be implemented in GAMS, Python or Matlab depending upon the background of the successful candidate.

Expected results
The expected results include relevant literature review, the formulation of the optimization problems and their implementations as well as their evaluation against a benchmark of a completely price-taker producer.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization

Trading Strategy of a Wind Power Producer in both Futures and Day-ahead Markets

Supervisors: Pierre Pinson, Athanasios Papakonstantinou, Stefanos Delikaraoglou
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Wind power generators trading their production in the day-ahead (spot) market are exposed to significant uncertainty due to price volatility and partial predictability of their actual output. In order to reduce their risk exposure, they can hedge their positions participating in the futures market which allows them to sell their energy production at fixed prices spanning a pre-specified time period, e.g., one day or one week before their participation in the day-ahead market. However, during periods of high spot market prices this strategy may result in loss of profits. Therefore, the goal of a wind power producer is to find the optimal involvement in each trading floor in order to maximize his expected profit over a given planning horizon, while controlling the risk of profit variability.

Objectives
In this context, the main objective of this MSc project is for the student to explore the interconnection between the financial (e.g. NASDAQ commodities OMX) and electricity (day-ahead) markets, and to be able to formulate an optimal trading strategy for a wind power producer participating in both those markets.

Methodology
This problem can be casted as a two-stage stochastic programming model where the first stage represents the participation in the financial market and the second stage represents the day-ahead market offers. This model can be further improved by considering a 'rolling planning' type of operation where the position in the futures market will be re-assessed based on updated wind power and price forecasts. The trading strategy will be evaluated using historical data from Nord Pool's day-ahead market (Elspot) and financial power market contracts from NASDAQ as well as wind power forecasts and measurements. The optimization models may be implemented in GAMS, Python or Matlab depending upon the background of the successful candidate.

Expected results
The expected results include relevant literature review, the formulation of the optimization problems and their implementation as well as their evaluation against a benchmark where a wind power producer trades his output only in the day-ahead market.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization and statistics

Development of an Open-source Platform for Wind and Solar Probabilistic Forecasting

Supervisors: Pierre Pinson, Emil B. Iversen
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context

Wind and solar power generation is spreading rapidly, inducing a number of challenges in power system operations and electricity markets. Forecasting is seen as a crucial input for nearly decision-making problems related to wind and solar power management. Forecasts may take various forms, while being either deterministic or probabilistic. Many academics and companies have developed solutions for wind and solar power prediction with lead times between a few minutes and several days ahead over the last 10-15 years. However, there is no commonly accepted open-source platform that would permit to generate such forecasts in a comprehensive, transparent and reproducible manner, to be used as input to operations and planning studies considering future penetration levels for such renewable energy sources. This is while there is an increasing need for such a platform and forecasting tools. Our group at DTU Elektro, CEE, has worked on developing a first version of an open-source platform, while producing results for the whole Western US in order to illustrate and verify the quality of the forecasts produced. Future plans are to extend that platform so that it may be used for as many locations as possible around the world, by both scientists and practitioners.

Objectives

In this context, the main objective of this MSc project is for the student to contribute to the development of this open-source platform, combining development of methods to improve the forecasts and their implementation. Different case studies may be considered, e.g., in Europe, Australia or the US.

Methodology

For the present MSc thesis project, emphasis will be placed on probabilistic forecasting approaches, permitting to inform about the whole range of future power production levels. These forecasts will take the form of both probability distribution functions and space-time scenarios. The most interesting part of these developments will focus on proposing fully data-driven techniques allowing to adapt the modeling and forecasting techniques to any site (and aggregation of sites), by adaptively estimating clear-sky models for the case of solar power, and spatio-temporal dependence structures for both wind and solar power generation.

Expected results

The expected results include relevant literature review, the formulation of the methods for issuing the probabilistic forecasts and scenarios, their implementation in the platform as well as their evaluation against a various benchmarks.

Prerequisites

Power systems operations, energy systems modeling, energy markets, basics of optimization and statistics

Revenue Adequacy and the Missing Money Problem in Highly Renewable Electricity Systems

Supervisors: Pierre Pinson, Tue V. Jensen
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
As the share of variable renewable energy sources (VRES = wind and solar) increases in the energy system, conventional generators find themselves pushed out of the energy market for two main reasons. First, since VRES have low-to-zero marginal cost, they are willing to produce at any price, and will get scheduled before conventional generators. Second, the increase in supply lowers the electricity price. Conventional generators thus produce less, and at a lower profit when they do produce, cutting into their profit margin. This may lead the plants to be shut down. However, as the amount of VRES available varies from day to day, the conventional generators are still needed for times of low renewable production. If too many plants shut down, the system may be unable to supply demand. This is the missing money problem.

Two avenues are available to market operators to resolve this issue. One solution is the formation of a capacity market, where the market or system operator buys guarantees for the capacity of the conventional generators in the market, with participants pricing based on their missing money. Such a system is currently in use in several US and EU electricity markets. A second solution is for the market operator to procure strategic reserve, which is only utilized for hours of peak demand. This solution is employed in the Nordic countries. As the capacity of VRES increases, generators will experience fewer full-load hours and progressively lower electricity prices. This will increase the cost of sustaining capacity, effectively increasing the cost to society for VRES installation. At some VRES capacity, the benefit of increased VRES installation may be outweighed by the cost to ensure sufficient capacity is available for hours of low VRES production.

Objectives
This project seeks to examine the costs involved in running capacity support mechanisms under increasing VRES capacity, and to determine the break-point VRES penetration where each mechanism becomes impractical.

Methodology
The assessment requires estimation of the fixed costs of market participants, the simulation of market outcomes under uncertain renewable generation, and modeling of the two support mechanisms. For the latter, modeling the decision of how much capacity to procure under each system, and the bids made by generators in each scheme is a non-trivial task, involving feedbacks between market simulations and a decision model. The simulations can be formulated as a sequence of two optimization problems for the day-ahead and real-time dispatches, and will be based on a recently developed large-scale model of the continental European transmission grid, which includes the full production characteristics of VRES.

Implementing the optimization models may be done in Python, Matlab or GAMS, depending on the background and preferences of the successful candidate.

Expected results
The expected results are literature reviews on capacity support systems and fixed cost estimations, the formulation of models of the energy market and capacity support system, and the evaluation of the cost of such a system under increased VRES penetration.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization.

Distributed Learning in Renewable Energy Forecasting

Supervisors: Pierre Pinson, Emil B. Iversen
Group: Energy Analytics & Markets, Centre for Electric Power and Energy, Department of Electrical Engineering

Context
Wind and solar power generation is spreading rapidly, inducing a number of challenges in power system operations and electricity markets. Forecasting is seen as a crucial input for nearly decision-making problems related to wind and solar power management. Forecasts may take various forms, while being either deterministic or probabilistic. Many academics and companies have developed solutions for wind and solar power prediction with lead times between a few minutes and several days ahead over the last 10-15 years.

One of the main challenges in forecasting renewable energy generation today is to adapt to the availability of large amounts of data, with high temporal resolution and for many sites. This is while the modeling and forecasting methodologies should make optimal use of this data at minimum computational costs. The availability of such large amount of data may also be seen as an opportunity for a change of paradigm in the way forecasting is done and considered. While forecasting has mainly been a centralized task so far (say at the level of a portfolio manager or system operator), the proposal of the thesis is to induce a paradigm change by considering that the whole forecasting problem should be distributed, as in problem of learning on a distributed sensor network.

Objectives
In this context, the main objective of this MSc project is for the student to propose an approach for distributed learning with application tor renewable energy forecasting, building on recent development on distributed optimization and network science. For the application of the methods and the validation of the proposal, different case studies may be considered, e.g., in Europe, Australia or the US.

Methodology
For the present MSc thesis project, emphasis will be placed on various approaches to distributed learning, combining ideas from distributed optimization and network science. In the first stage, the forecasting problem will be formulated in such a way that it will be possible to decompose it and share it. Known methods will be applied for that purpose. An additional complexity will arise when aiming to make this distributed learning as cheap as possible, by making it recursive and adaptive, while still being distributed. Finally, it is aimed to figure out how this learning distribution should be optimally done, in an effort to minimize the potential needs for measuring and communicating information at all potential sites considered (these may be thousands or more!).

Expected results
The expected results include relevant literature review, the formulation of the methods for distributed learning and application to renewable energy forecatsing, their implementation as their evaluation for real-world test cases.

Prerequisites
Power systems operations, energy systems modeling, energy markets, basics of optimization, statistics or data-mining