MARKET INTEGRATION OF WIND POWER

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ABSTRACT

A satisfying analysis of the impacts of introducing significant shares of wind power in a electricity system requires that the stochastic nature of wind power production is taken into account. An hour-per-hour stochastic, optimisation model of the electricity systems in Denmark, Finland, Germany, Norway and Sweden has therefore been developed in the WILMAR project. To our knowledge it is the first model of this type to be developed for a large electricity system. Treatment of large hydropower reservoirs requires optimisation of the use of water over a yearly or longer time horizon. Therefore the hourly, stochastic optimisation model is combined with another stochastic, optimisation model focusing on calculating the option value of stored water dependent on the time of year and reservoir filling. Finally a third set of models have been developed that make regional wind power production forecasts, and reduces these forecasts into a scenario tree used by the hourly, stochastic optimisation model. These models are combined with databases into a Planning tool enabling analysis of liberalised, electricity systems with large shares of hydropower production and fluctuation power production. Considerations about how to represent a liberalised, electricity system in the hourly, stochastic optimisation model ended up in the modelled electricity system consisting of three markets: a day-ahead market, a balancing hour-ahead market, and finally a market for daily reservation of primary reserves. By dividing the geographical area into regions connected with transmission lines the Planning Tool can investigate the effect of bottlenecks and investments in transmission capacity.

WIND POWER, INTEGRATION, STOCHASTIC OPTIMISATION, FORECASTS, POWER MARKET

Parts of the text in this paper have previously appeared in previous WILMAR presentations, e.g. the first WILMAR newsletter and deliverable 3.2 of the WILMAR project (see www.wilmar.risoe.dk).

1. INTRODUCTION

The introduction of large amounts of intermitting renewable power production such as wind power might interfere negatively with the technical and economical performance of the power system:

- If power from intermitting sources in periods exceeds the local/regional power demand congestion of transmission lines might cause technical instability of the power system.
- Fluctuating and difficult predictable power production from intermitting sources requires additional regulatory capabilities of the conventional power system, implying extra costs.
- Large amounts of wind power with low marginal costs might have considerable impact upon the functioning of the power spot market, including volatility of spot prices.

The reality of these problems is already encountered in Western Denmark, and the development of wind power is expected to continue. In recent years, a number of European countries have experienced a fast growth in the installation of wind turbines, e.g., Germany, Spain and Denmark. In all likelihood, this fast growth rate of wind power will continue in the years to come, which is also reflected in the 40000 MW target for wind power in 2010 in EU, put forward in the White Paper on renewables from the European Commission.

This fast expansion of wind power is to be introduced in electricity markets that are undergoing a process of market liberalisation as mentioned above. A consequence of the liberalisation is that the dispatch of the power plants in the electricity systems are increasingly being controlled by trading on power pools, as it is seen in a number of European countries: England, Poland, Germany, Sweden, Norway, Denmark, Finland, Spain and the Netherlands.

The other units must counteract fluctuations in the wind power production in the power system to maintain the stability of the power system. Therefore, larger amounts of wind power will require the presence of larger amounts of frequency-responding spinning power reserve[1] and supplemental power reserve[2] in the power system compared to a situation without wind power. The introduction of wind power, therefore, put strains on the performance of the other power-producing units in the electricity system.

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[1] The frequency-responding spinning power reserve in a power system is (normally large) power plants that respond with fast, automatic changes in their power production to changes in the electrical frequency of the grid.

[2] The supplemental power reserve is power plants that can adjust their power production within 15 minutes. The system operator activates them manually.

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On the economical side, the introduction of substantial amounts of wind power will influence the price on the spot market, because the marginal production price of wind power is very low (mainly operation and maintenance costs). The average price level on the regulating power market is expected to increase, because the unpredictability of wind power will cause trading of larger amounts of supplemental power compared to a situation without wind power. The handling of the technical impacts will, in some cases, be associated with an extra cost, as in the case of dedicated wind power integration measures such as reinforcement of transmission grids or construction of electricity storages.

Wilmar is an acronym of *"Wind Power Integration in Liberalised Electricity Markets".* The project was started in 2002 and is funded by the EU's 5th Research programme on energy and environment. Risø National Laboratory is co-ordinator of the project and partners include SINTEF, Kungliga Tekniska Högskola, University of Stuttgart, VTT, Nord Pool Consult, Technical University of Denmark, ELSAM A/S and Elkraft-System A/S.

The aim of the Wilmar project is to investigate the above-mentioned technical and economical problems related to large-scale deployment of renewable sources and to develop a modelling tool that can handle system simulations for a larger geographical region with an international power exchange. When finalised, the Planning tool will be made public available to actors within the power sector, including power system operators, energy authorities, power producers and other potential investors within this field.

The main methodological focus of the Planning Tool is to include information contained in wind power production forecasts in the decision support tool. Recently the work with wind power production forecasting has been extended from only aiming at forecasting the expected wind power production to forecasting a distribution of future wind power productions. By using stochastic optimisation in the Planning Tool the distribution of wind power production forecast errors are taking explicitly into account when making dispatch decisions for the power plants in the system, i.e. the dispatch decisions are more robust towards wind power production forecast errors than decisions taken with a model not using stochastic optimisation.

The design of the Planning Tool is presented in this paper. Section 2 presents the basis modelling assumptions used in the model design. In section 3 an overview of the Planning Tool is given with a focus on the Joint Market model and finally section 4 indicates the future work with the Planning Tool.

2. GENERAL MODELLING ASSUMPTIONS

Number of Markets for Physical Delivery of Electricity

Three electricity markets are included in the Planning Tool, namely:

1. A day-ahead market for physical delivery of electricity where the Elspot market at Nord Pool and the EEX market at Leipzig, Germany are taken as the starting point[3]. This market will in the following text be called the **day-ahead market.**
2. An intra-day market for handling deviations between production and consumption agreed upon on the day-ahead market and the realised values of production and consumption in the actual operation hour. Regulating power can be traded up to the start of the actual operation hour. Hourly mean-values are used meaning that there is no inter-hour regulation happening in the model. Both flexible producers and flexible consumers offer regulating power on this market, which in the following text is called the **intra-day market.** The demand for regulating power is defined by the forecast errors connected to the wind power production.
3. A day-ahead market for automatically activated reserve power (frequency activated or load-flow activated). The demand for these ancillary services is determined exogenously to the model. This market will be called the **ancillary services market**.

Finally, these markets will cover the whole geographical area, i.e., we assume that the day-ahead market at Nord Pool and EEX can be analysed as one market[4], and the same applies to the intra-day market.

Short-Term Marginal Pricing

We assume perfect competition where power suppliers offer electricity to the **short-term marginal cost of generation** of the power plants. This assumption covers both the day-ahead and the intra-day market. For a given power plant, the short-term marginal cost of generation covers the price of the fuel input and the variable operation and maintenance costs, including start/stop costs. Investment costs and fixed operation and maintenance costs are not included in the short-term marginal costs.

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[3] The model must enable changes in the spot market trading rules such as a change from a day-ahead market to an hour-ahead market.

[4] Although we assume one market covering the whole geographical area, this does not imply that we will only have one market price in the whole area. Exchange restrictions between areas will result in different area prices.

3. OVERVIEW OF THE PLANNING TOOL

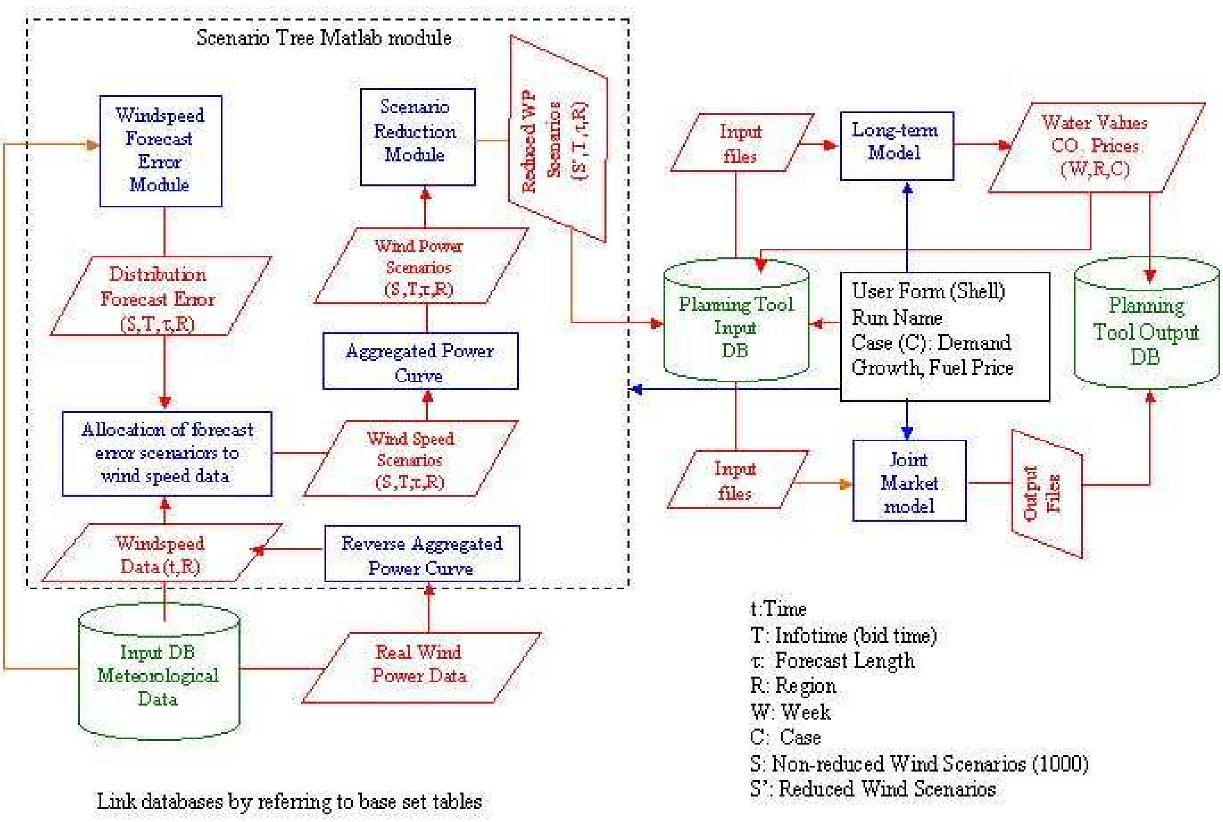

Figure 1: Overview of the WILMAR Planning tool. Blue boxes are models, green cylinders are database, red parallelograms are exchange of data between models and between models and databases. The black square is the User Shell that controls the selection of cases and running of the models. The red arrows indicate data exchange, and the blue arrows indicate the flow of commands from the User shell to the models.

An overview of the design of the Planning Tool is given in Figure 1. The Planning Tool consists of three databases, three sub-models[5] and a User Shell. Below the functionality and design of each module is explained.

Long-term model

Due to the existence of hydro reservoirs and limitations on the amount of water inflow to the hydropower system, the use of hydropower must be optimised over a one-year (or longer) horizon. Furthermore, if we assume the existence in the model of a fixed CO_2 quota for the North European electricity system, the CO_2 emissions from the power plants will be subject to a long-term (yearly) restriction.

The Long-Term Model will optimise the use of water inflow and CO_2 quotas over a one-year horizon. The input from the long-term model to the Joint Market model will be one table with the water values (opportunity costs of using stored water) as a function of reservoir filling and time of year, and another table with the CO_2 shadow prices as a function of the fraction of the available CO_2 quota still not used and the time of year.

The Long-term model gets input data from the Planning Tool Input database and delivers output to the Planning Tool output database (see Figure 1). The sharing of input data between the Joint Market model and the Long-term model

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[5] The Scenario Tree Matlab module is counted as one sub-model, because the sub-models constituting this module are all written in MatLab and have been merged into one.

secures consistency between the models with regard to input data. The functionality and design of the Long-term model is briefly described in [1].

Joint Market model

The Joint Market model simulates a perfect market place with four types of products: day-ahead market power, district and process heat, regulating power on the intra-day market and ancillary services. The actors on the market place maximise their profit through trade on the day-ahead market, the intra-day market and the ancillary services market. Due to the perfect market assumption, this is equivalent to maximising the sum of consumer and producer surplus. For all operational hours in a bidding period on the day-ahead market, the Joint Market model optimises the sum of the consumers' and producers' surplus on the heat markets, the day-ahead market and the intra-day market. The optimisation is done subject to different constraints such as transmission constraints in the electricity system and capacity constraints of storage and generating technologies. The Joint Market model is a stochastic linear programming model where the optimisation is done subject to a stochastic regulation need on the intra-day market. The first version of the Joint Market model only considers the contribution of the wind power production to the stochastic regulation need, but later versions can include other stochastic parameters such as the power demand. The functionality and design of the Joint Market model is described in more detail in [2].

The model output consists of:

- Day-ahead market production plan for the next bidding period, i.e., how much to produce on the different generating units according to the market clearance on the day-ahead market.
- Hourly day-ahead market prices in each region.
- Hourly transmission between each region.
- Regulating power capacities and regulation power prices in each hour in the bidding period.
- Distribution of ancillary services on power plants.

Geography

The Joint Market model uses the following types of geographical units: **countries, regions and areas**. The relations between these geographical entities are such that a region contains areas, and a country contains regions. The regions are introduced to handle electricity *transmission* aspects and correspond to bidding areas as seen on the Nord Pool market. The *distribution* of electricity within a given region is not included in the model[6], but different regions can exchange power. The areas are the smallest geographical entities. The data given at the level of areas include those related to heat demand and heat distribution.

Time

The finest time resolution in the Joint Market model is one hour. This is in line with the functioning of the present day-ahead market(s).

Decision Structure

In any model, it is important to understand the decision/stage structure of the problem, i.e., when must decisions be taken, and when does new information arrive that enables new and improved decisions to be taken?

At Nord Pool, bids for the Elspot market must be each day delivered at noon thereby covering the production hours of the next day, i.e., a 24 hour day-ahead market bidding period with a time lag of 12 hours between bid submission and start of the day-ahead market bidding period. Approximately two hours following bid submission, Nord Pool has cleared the Elspot market and returned the amounts sold to and bought from each actor for each hour in the day-ahead market bidding period (see Figure 2).

Operated by the TSO's, a regulating power market runs in parallel with the day-ahead market where bids for up or down regulation to be activated in the actual operation hour must be submitted one hour before the actual hour. The TSO can activate the up or down-regulation bids with a 15 minutes notice, i.e., the time resolution in the regulating power market is below one hour. The bids submitted to the regulating power market must take the obligations from the day-ahead market into account, i.e., the amounts sold/bought on the day-ahead market influences what can be offered on the regulating power market.

[6] At least only as a distribution loss factor and a distribution tariff.

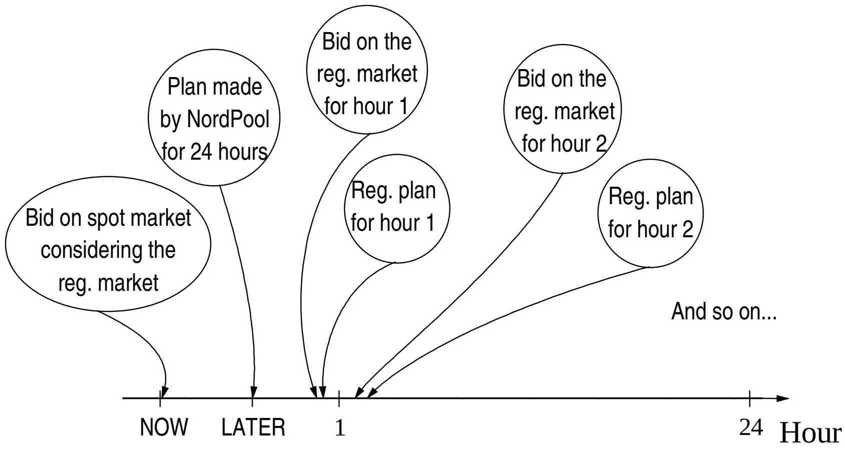

Figure 2: llustration of the time structure of the bidding procedures on the Elspot market at Nord Pool and the regulating power markets in the Nordic countries [3].

New information arrives on a continuous basis and consists of updated information about the operational status of production and storage units, the operational status of the transmission and distribution grid, updated demand for heating, electricity demand and wind power production forecasts and updated information about day-ahead market and regulating power market prices. Most actors only have access to a limited subset of this information, e.g., an actor only knows the detailed operational status of units owned by him.

Furthermore, because of time-overlapping restrictions, such as storages (heat, electricity), water reservoirs and start/stop times and costs, the operation strategy of a unit needs to be simultaneously decided upon for several production hours.

All in all, a producer with flexible production units making bids to the day-ahead market faces a quite difficult decision problem, because of time-overlapping restrictions on the production output and because the expected profit from participating in the regulating power market in the production hours in the day-ahead market bidding period also need to be taken into account. This decision problem can be formulated mathematically as a multi-stage, stochastic optimisation problem. Multi-stage because bids to the regulating market are made each hour and the day-ahead market bidding period covers 24 hours, and stochastic because the regulating need in a given operation hour is stochastic depending among other things on the accuracy of wind power production forecasts.

Discrete approximations of the distributions of the stochastic parameters are standard in stochastic dynamic programming techniques and will also be employed in the Joint Market model. However, such discrete, stochastic optimisation models quickly become intractable, since the total number of scenarios has a double exponential dependency in the sense that a model with $k+1$ stages, m stochastic parameters, and n scenarios for each parameter (at each stage) leads to a model with a total of $s = n^{m^k}$ scenarios. It has, therefore, been necessary to simplify the decision structure of the day-ahead market bids in the Joint Market model.

The decision structure in the Joint Market model is illustrated in Figure 3, which shows the scenario tree for four planning periods covering one day. A scenario consists of a vector of wind power production forecasts for all regions. For each rolling planning period, a three-stage, stochastic optimisation problem is solved having a deterministic first stage covering 6 hours, a stochastic second stage with three scenarios covering 6 hours, and a stochastic third stage with 9 scenarios covering a variable number of hours according to the rolling planning period in question. In rolling planning period 1, the production and consumption volumes on the day-ahead market are determined. During the subsequent rolling planning periods, the production and consumption variables on the day-ahead market are fixed on the values found in rolling planning period 1, so that the obligations on the day-ahead market is taken into account when the optimisation of the intra-day trading takes place.

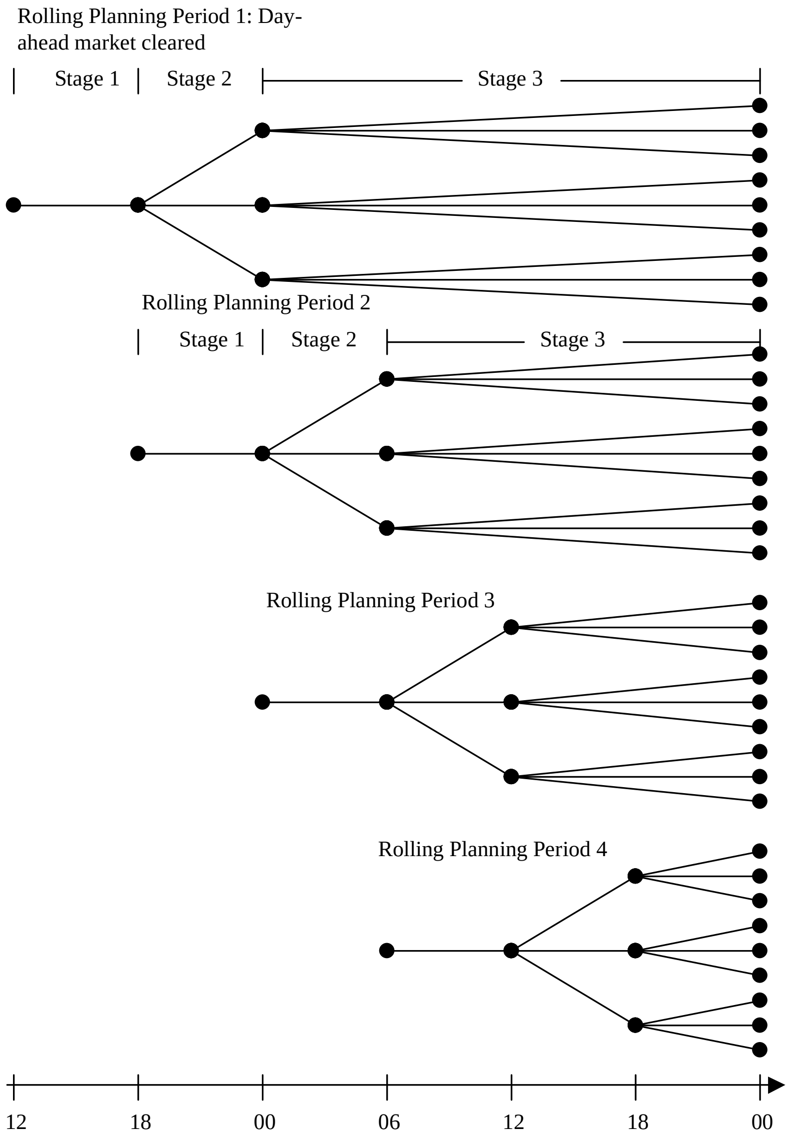

Figure 3: Illustration of the rolling planning and the decision structure in each planning period within a day.

The optimisation done in planning period 1 determines the production, consumption and prices on the intra-day market in hour 12 to 17. The optimisation done in planning period 2 determines the same for the hours 18-23, planning period 3 determines the same for the hours 00 to 5 and finally, planning period 4 for the hours 6 to 11.

By stepping through the planning periods, the production, consumption, exchange and prices on the day-ahead, intra-day and ancillary services market are in this way determined for a given period of time.

The functioning of the model with the implemented decision structure can be interpreted as one operator with full knowledge of the operational status of all units in the system trying to maximise the consumer and producer surplus in the market. When making bids to the day-ahead market (rolling planning period 1), the operator takes into account the intra-day market knowing that the production decisions related to the intra-day market can be changed twice during the day-ahead market period, namely 6 hours and 12 hours after submitting the bids to the day-ahead market. Furthermore, the wind power production in the first 6 hours is with certainty known, but subsequent hours have uncertain wind power production. After having received information about day-ahead market production and consumption volumes, the operator re-optimises the production decision on the intra-day market every 6 hours having the traded volumes on the day-ahead market as restrictions in the optimisation.

The Joint Market model gets input data from the Planning Tool Input database and delivers output to the Planning Tool output database (see Figure 1). The Joint Market model is being tested in these months, and hopefully the current model design will be the final one, except for minor corrections.

Scenario Tree MatLab Module
The Scenario Tree MatLab Module constructs the scenario trees for the wind power production forecasts that are used in the Joint Market model. The functionality of the module is described in more detail in [2]. It is implemented in Matlab and compromises five sub modules:

- Wind Speed Forecast Error Module
- Reverse Aggregate Power Curve Module
- Module for allocation of wind speed forecast errors to measured wind data
- Aggregated Power Curve Module
- Scenario Reduction Module

The data flow within the Scenario Tree Tool is working in the following way:

- The needed data (wind speed and wind power time series, trend of the wind speed forecast error and correlations of the forecast error between wind speed time series) are read into the Scenario Tree Tool.
- If a sub-region is described with wind power data, the time-series is transferred into a wind speed time-series with the Reverse Aggregated Power Curve Module.
- Based on the trend of wind speed forecast errors and their correlations the wind speed forecast errors are estimated and a specified number of forecast scenarios (actually 200) is drawn (see [4] for a description of this model).
- The forecast error scenarios are allocated to wind speed time-series.
- The wind speed scenarios are converted to wind power scenarios with the Aggregated Power Curve Module. This module determines a smoothed wind power converter curve related to the size of the treated sub-regions (see [5] for a description of this model).
- The wind power scenarios are reduced to nine scenarios considering the probability of occurrence of each scenario [2]. Finally the scenarios are allocated to the predefined scenario tree structure.

User Shell
The User Shell does the following:

- Enables the selection of the case (i.e. the scenario) to be investigated by the Planning tool. A case consists of a selection of historical data that give the time variation of different parameters (e.g. electricity and heat demand) and a selection of scenario parameters (e.g. yearly electricity consumption in year 2010, capacity of power plants in year 2010).
- Transfer the case data to the Planning Tool input database, activate the queries generating the input files to either the Joint Market model or the Long-term model.
- Activate the model to be run (Scenario Tree MatLab module, Joint Market model and/or Long-term model).
- Activate the Planning Tool output database, which reads the output files from the model and aggregates and visualises the results using predefined forms and queries.

As mentioned the User Shell transfer data to the Planning Tool Input database, and it exchange commands with the three sub-models and the two other database.

Input Database Meteorological Data
The Input Database Meteorological Data is primarily designed to store the data needed within the Scenario Tree Tool. This contains of:

- Measured wind speed data and wind power production time series at the level of sub-regions (each model region can be subdivided into smaller sub-regions) for the Nordic countries and Germany.
- Parameter data for the wind speed measurement stations (e. g. allocation to a sub-region) and wind power locations (e. g. installed capacities, size of the sub-region that is described by the individual wind power location).
- Wind speed forecast errors related to each wind speed measurement station.
- Correlations of wind speed forecast errors between the individual wind speed time series. In the actual version of this database the correlations are identical for all measurement stations.
- Further parameters (e. g. the used characteristic curve of the used wind power converters, Weibull parameters, the structure of the scenario tree).

Planning Tool Input database
The Planning Tool input database stores the data needed to run the Joint Market model and the Long-term model, except temperature and wind data that are stored in the Meteorological Input database. Using case data transferred from the User Shell, the database selects the subset of the total data that is needed as input in a specific model run, it scales the historical time variations according to the chosen scenario parameters, and it convert the data into the format needed by the GAMS modelling language. The output from the database is a series of text files formatted such that the GAMS programme can read the files.

Planning Tool Output database
The result of a run with the Joint Market model is written to a number of text files. Next the output database imports these text files in pre-specified tables. The output consists of the values of consumption, production, transmission and storage variables and the marginal values of balancing equations interpreted as prices. Apart from this also some of the input data is written in text files and imported into the output database. Doing this enables that the output database can be operated independently of the Wilmar Planning tool input database. In the database the model results are aggregated and visualized with the use of queries and forms.

4. FUTURE DEVELOPMENT OF THE PLANNING TOOL

The different parts of the Planning Tool is being finalised in the coming months. The testing of the tool has started in a corporation between the TSO, the power producer and the research organisations involved in the WILMAR project. After the testing of the Planning Tool, the tool will be used to analyse the technical and markets impacts of wind power, the integration costs of wind power and the performance of integration measures. Finally a lot of effort will be put into the documentation of the tool and dissemination of the results from the analysis.

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