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Abstract:

The Wilmar Planning Tool is developed in the project Wind Power Integration in Liberalised Electricity Markets (WILMAR) supported by EU (Contract No. ENK5-CT-2002-00663).

This report is the public version of the Final Technical report in the Wilmar project where the scientific and technical results are described.

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Preface

The Wilmar Planning Tool is developed in the project Wind Power Integration in Liberalised Electricity Markets (WILMAR) supported by EU (Contract No. ENK5-CT-2002-00663).

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1 Summary

A Planning tool enabling model based analysis of wind power integration issues has been developed in the project. An overview of the sub-models and databases constituting the Planning tool is given in Figure 1.

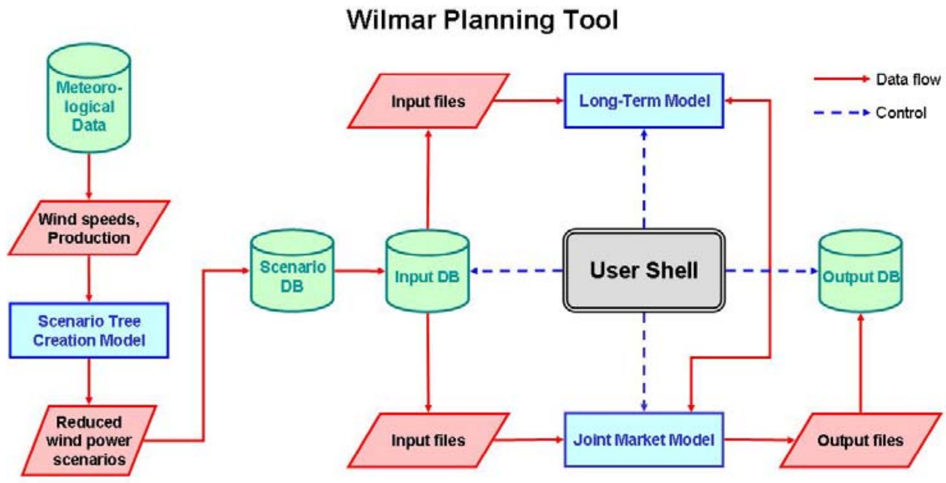


Figure 1 Overview of Wilmar Planning tool. The green cylinders are databases, the red parallelograms indicate exchange of information between sub models or databases, the blue squares are models. The user shell controlling the execution of the Wilmar Planning tool is shown in black.

The Joint Market model is a linear, stochastic, optimisation model with wind power forecasts as the stochastic input parameter, hourly time-resolution and covering several regions interconnected with transmission lines. It has been tested on German and Nordic data. A wind speed forecast model has been developed, which incorporates the correlations between wind speed forecast from one time step to the next and the correlations between wind speed forecasts in different regions. The wind speed forecast model can be fitted to reflect the precision of existing forecast tools. A model for converting the wind speed forecast into wind power production forecasts using an aggregated power curve has been completed. Wind power production data from the Nordic countries has been collected and analysed in respect of the extent of variations and smoothing effect in the large scale, geographically dispersed production. Treatment of large hydropower reservoirs requires optimisation of the use of water over a yearly or longer time horizon. Therefore the Joint Market model is combined with another stochastic, optimisation model that focus on calculating the option value of stored water dependent on the time of year and reservoir filling. A first version of this “long-term” model has been developed. Extensive data collection has been undertaken and three databases have been designed to store the input data and one to store the output data from the Planning tool. A user shell controlling the selection of which case to run with the Planning tool in terms of countries included, simulation year and time period analysed, together with selection of scenarios for fuel prices and CO2 emission permit prices development has been developed.

A stepwise power flow model used to study frequency changes from minute to minute in a Nordic power system as a function of changes in load and available production capacity as well as the availability of regulating power in the system has been developed. This model provides a suitable level of modelling in order to study basic problems related to primary and secondary control and provision of reserves. The output from the Planning tool in terms of production, load and wind power production for two consecutive hours of interest are used as input to the frequency stability simulations. Algorithms for semi-automatic conversion of the output from the Planning tool to the input format of the stepwise power flow model have been developed. This interaction between the Planning tool and the stepwise power flow model constitutes the main link between the WP6 (planning models) and WP5 (stability analysis).

Through simulations it has been shown how large-scale integration of wind power in Norway may influence the damping of inter-area oscillation modes in the Nordel system. In the transient stability studies it was considered how a future 198 MW offshore wind farm in Eastern-Denmark would influence the post-fault conditions in the Nordel system. These analyses have been published in articles.

A scenario for the base configuration of the North European power system in 2010 has been agreed upon. This scenario is combined with several scenarios for the installed wind power capacity in 2010.

Several conference papers presenting results generated with the Planning tool have been written, and several articles are in progress. The results focuses on 1) the performance of integration measures such as heat pumps and extension of transmission lines and 2) the integration costs and avoided costs of increasing the share of wind power in the North European power system.

The Planning tool has been made openly available on www.wilmar.risoe.dk such that organisation outside the project consortium can benefit from the work. Reports from the project are also available on this homepage. Analysis based on the tools developed in the project combined with discussions in the project team have been used to identify how the electricity markets should be organised to enable a cost-effective integration of wind power in large liberalised electricity systems. The main recommendations concern improving the use of transmission capacity, making sure that all regulating power is bid to markets, enhancing flexible demand and storage participation in markets, reducing imbalances caused by wind power by aggregating wind power production and bidding closer to delivery hour, and make sure that imbalance settlement charges reflect the system imbalance costs actually incurred.

Use and further development of the Planning tool will be continued in a new EU-funded research project named SUPWIND scheduled to start in the beginning of 2006. Based on the planning tool developed in the WILMAR project, a set of tools is developed which support Transmission System Operators (TSOs) and other stakeholders in their operational and strategic decision making related to the integration of high shares of wind or other fluctuating renewables. The evaluation of regional and trans-national transmission line investments caused by large scale introduction of wind power will be analysed. Furthermore the project aims at demonstrating the applicability of tools for the operational management of grids and power plants under large scale wind power generation.

Several Wilmar partners will continue their work with the Planning tool and the other models used in Wilmar in nationally and internationally funded projects like collaboration in the International Energy Agency (IEA) framework.

2 Objectives and strategic aspects

2.1 Socio-economic objectives and strategic aspects

The liberalisation process has proceeded rapidly, especially in the northern part of Europe. Those countries involved in this project are close to establish an integrated power exchange covering a large geographical area and at the same time involving quite different energy systems: Norway and Sweden have large amounts of hydro power, while Finland, Germany and Denmark are mostly based on conventional fossil fuelled-fired power plants. Finally, both Germany and Denmark experience very rapid developments of wind power and already have large capacities of wind turbines. In Denmark problems of “absorbing” power from intermitting sources in the power system have already been encountered and if not solved these might give rise to essential systems cost in the near future. If the actors at the power field do not handle these problems, they might create important barriers for the future deployment of renewable energy sources.

In the European Union policy the development of renewable energy technologies is an important issue, not only in meeting the EU internal goals for the deployment of renewables, but especially in relation to achieving the Kyoto targets for emission-reductions. Moreover the deployment of renewable technologies adds to diversification on energy sources and increased independence of fossil fuels and thus to an increased security of supply.

This project attempts to reveal if any systems barriers exist, that could prevent a deployment of renewable technologies, opposed to the initiatives as given by the overall EU policy. To identify such barriers an effective modelling tool is developed, making it possible for the key actors within the electric power system (systems operators, power companies, energy authorities etc.) to be pro-active and aware of the problem at an early stage, thus creating a firm basis for solving the problem in a cost-effective way. Thus this project will develop strategic planning tools, that can be essential for paving the way for efficient and cost-effective development of renewable energy sources and thus for achieving low-cost emission reductions in the future.

Finally, the project will give recommendations to the EU-commission regarding the possibilities of handling these problems of system regulations within a policy context.

2.2 Scientific/technological objectives

The scientific/technological objectives of this project are:

1. To develop a strategic planning tool to analyse the integration of renewable power technologies to be applied by system operators, power producers, potential investors in renewable technologies and energy authorities.

2. To analyse the technical impacts connected to the introduction of substantial amounts of wind power in the northern part of the European electricity system – covering the Nordic countries plus Germany. The issues of system stability connected to the fast (below 10 minutes) fluctuations in the wind power

production will be analysed, as well as the issues of achieving an hour-per-hour power balance in the electricity system. Also the long-term issue of securing the energy balance irrespective of the variation in the wind power and hydro power production from year to year will be analysed.

3. To analyse the performance of different integration measures in a liberalised electricity system. Both the possibilities for integrating fluctuating power production by optimising the interaction of the existing units in a given electricity system, the possibilities lying in power exchange between regions, and the performance of dedicated integration technologies like electricity storages will be evaluated. Special attention will be given to interactions between the integration measures and the organisation of the power pool.

4. To quantify the costs connected to the integration of large shares of wind power in a liberalised electricity system, i.e. to answer the question what does it cost to integrate a certain amount of wind power in a liberalised energy system?

3 Scientific and technical description of the results

The description of the scientific and technical results achieved in the project falls naturally into four groups:

1. The work taking place in WP5 related to system stability issues, which can be further subdivided into model development and analysis related to frequency stability and usage of primary and secondary reserves, small-signal stability and transient stability. Furthermore a method for using results from the Wilmar Planning tool as input data to the WP5 simulations has been established.

2. The work involved in the development and usage of the Wilmar Planning tool, i.e. work taking place in WP2, WP3, WP4, WP6 and WP8. This work can be further subdivided into development of the Joint Market model, development of the Long-term model, construction of scenario trees for wind power production forecasts, collection and storage of input data, design of output database, design of user shell, analysis of wind power integration issues with the Wilmar Planning tool.

3. Analysis of the distribution of integration costs in WP7.

4. Formulation of recommendations regarding organization of electricity markets and power pools to enable cost effective integration of wind power (WP9).

3.1 Analysis of system stability

3.1.1 Objectives and overview of approaches taken

The main objective of the WP5 work in the WILMAR project has been to:

1. Identify and quantify potential system stability problems in particular related to large-scale integration of intermittent renewable energy generation into the power system.

2. Identify and evaluate various solutions to eliminate/reduce the problems.

The purpose of WP5 is to perform different types of stability studies with large scale wind power in the Northern European system. This is important in order for the different stakeholders to make the correct decisions concerning wind power integration.

For a transmission system operator stability studies will be useful in order to assess:

- How much wind power can be integrated from an operational security point of view?
- How much operating reserves are needed?
- Congestion management.
- Secondary control and protection issues.
- System stability (Voltage stability, Angle stability).

From the generation owner/wind farm developer point of view the system stability studies are useful in order to make assessments regarding:

- Choice of wind farm technology (control systems, protections, etc.).
- Additional costs (or reduced income) due to network constraints.

The stability studies concerning frequency and secondary control have been performed based on input from Wilmar Planning tool simulations. The issues relevant for analysis by the Wilmar Planning tool and WP5 simulations are indicated in Figure 2. For chosen consecutive hours simulated in the Wilmar Planning tool, the effects that may occur within these hours due to the dynamic changes in wind, load, and production are simulated in WP5. The idea is to get an indication if the strategy chosen for the balancing power market in the Wilmar Planning tool is able to deal with the continuous changes in load, wind and other power production.

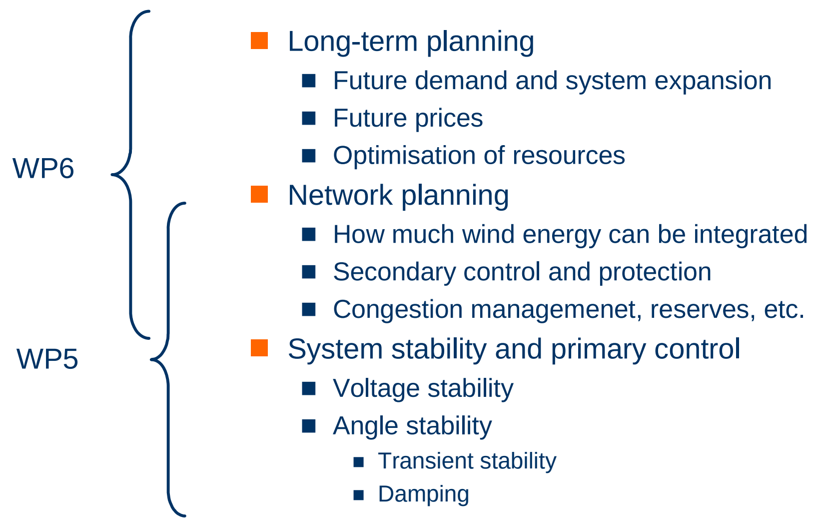


Figure 2 Subjects of relevance for WP6 and WP5.

The main approach in the WP5 studies is to use a simplified or reduced model [Bakken 1997] of the Northern European power system (23 generator model) to analyse different stability problems. The reduced model has been established at SINTEF with the purpose of demonstrating some main dynamic properties of the Nordic power transmission system. Additionally, the equivalent network data (lines and transformer impedances) are adjusted to fairly well reflect the flow of power in the different corridors between the countries.

The chosen model is utilised in different computer programs to simulate different types of stability problems. With a large increase of installed wind power capacity in the Northern-European system, it is expected that there will be increased difficulties to keep the system frequency in the Nordel system within acceptable limits. It is therefore important to analyse the balancing power market in the context of keeping the system frequency within the requirements also for 2010 cases. Power flow on main transmission corridors will also be influenced by large scale wind power integration and acceptance of balancing power market bids. These are operational challenges that have been assessed as part of the case studies based on input from Wilmar Planning tool simulations.

A more general approach has been taken in the case study concerning small signal stability or power oscillation damping. In this context the most important issue was to investigate the general influence on the system damping with large-scale wind power integration in the system.

The work and results from WP5 have been documented in D5.1 in the Wilmar project [Norheim et al 2005].

3.1.2 The 23 generator model of the Northern European system

The basis for all simulations in WP5 is the 23 generator model of the Northern European power system. The 23 generator model determines the topology of the grid, where in the grid conventional production is located and where in the grid the loads are located. For the secondary control cases the output from the Wilmar Planning tool determines the amount of production and on which units, the amount and location of wind power, the bid list for the balancing power market, and the HVDC ramping. For the cases of analysing damping and transient stability selected data sets has been chosen out of the purpose of the simulations. In these cases the wind power were modelled according to the type of technology that were considered.

The 23 generator model has been developed in PSS/E at SINTEF Energy Research. The main motivation for developing the simple model of the Nordel system was:

- It was desirable to study slow dynamic phenomena as control of frequency and active power. Thus, a simpler model reduced the simulation time to acceptable levels.

In the context of the WILMAR project, the 23 generator model is suitable as it have a significant correspondence in power flow and in dynamic responses if comparing with a full scale model of the Nordel system. For analysis connected to secondary control the reduced size and still significant accuracy makes the 23 generator model favourable. In addition there is no restriction in distributing it among the different project partners (available full-scale models are restricted information and can not be distributed). Thus, the different partners could work on the same model as input for their simulation tools and the methods especially for simulation of long term stability could be compared. Furthermore, the data from Wilmar Planning tool to WP5 did not have to be converted to several models.

In the 23 generator model of the Northern European the lines and generators are located and adjusted in such a way that they to a significant degree reflect the real production and the most interesting bottlenecks in the Nordel system. The impedances are adjusted in such a way that the power flow to a significant degree will correspond to a full-scale model. Finally the dynamic models of the aggregates have been adjusted in such a way that the major dynamic properties of the 23 generator model reflect the major dynamic properties in the full-scale model.

The simplifications made in the model have their drawbacks as well. Actual regulating power is probably more limited than in the model. For example river systems have time lags for the ramp rate and thermal plants have restrictions that are not present in this level of aggregation.

In Figure 3 the locations of the different generators equivalents in the 23 generator model are shown. The node number of the different generators is also shown.

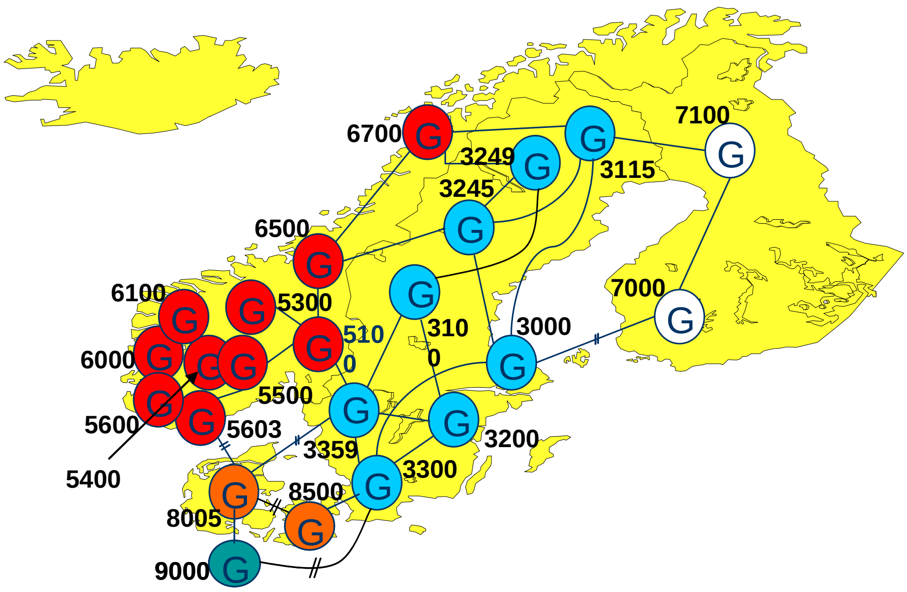


Figure 3 Location of generators in the 23 generator model.

3.1.3 Frequency stability studies

Within the WP5 activity in the WILMAR project the main focus has been on frequency deviation due to imbalance between production and load within simulated hours. A large scale integration of wind power in the Northern European system causes increased variation and increased unpredictability of the production compared to the present day situation. For this situation it is of importance to investigate if the power system is able to maintain a satisfying balance between production and load. This is measured by the frequency deviation from 50 Hz. In the NORDEL system it is required that the system frequency during normal operation should not deviate more than ± 0.1 Hz from 50 Hz. To prevent this from happen the transmission system operators (TSOs) trade secondary power reserves (minute reserves) on the regulating power market.

The analysis of frequency stability has focused on operating situations demanding up regulation of production, as it is judged by the project group that down regulation situations are considerable easier to handle, e.g. in worst case situations the wind power turbines can be down regulated.

Few tools exist to analyse secondary control problems. A new model called Stepwise Power Flow (SPF) has partly been developed through the WILMAR project. This model makes it possible to analyse the frequency deviations within a simulated hour when some key information about how the system changes is available as input data, i.e. the load change, wind power change, scheduled production change, and the bids on the balancing power market. In case of large frequency deviations balancing power is activated according to the bid list. This way it is possible to examine if there is a sufficient amount of balancing power available on the bid list. The main input data, such as the bid list, production plans, variation in load and wind power are available from the Wilmar Planning tool. Thus, the cases selected and simulated with the SPF routine will indicate if there are potential operating problems within the hour problems that are not possible to observe with simulation of the Wilmar Planning tool. Alternative approaches to the SPF routine were also performed in order to have a stronger validation of the results and methods. These models are long term simulation in the power system simulation tool PSS/E and LP optimisation with DC power flow.

Selected hours from the Wilmar Planning tool simulations have been selected for analysis with the WP5 frequency stability models. These hours are characterised by decreased wind power production throughout the hour and increased load. The hours with largest increase in demand from hour to hour in the historical time series are analysed. This way, it is expected to get a general impression (without an exaggerated amount of simulations), if the output results from the Wilmar Planning tool are reasonable with respect to frequency stability.

One case using the historical time series from 2001 and the 2001 power system configuration, and two 2010 cases (base wind and 10% wind) was analysed. The 2010 cases are presented in Section 3.3.

3.1.4 Stepwise power flow model

In the case of power and frequency control, typically Fast reserves, Secondary control and AGC (Automatic Generation Control) are difficult to handle in standard system stability tools since these operate in the 5-15 minutes range, sometimes longer. Adding the coordination with generation scheduling and load forecast errors the time span is even longer. To enable such studies of the power system including Secondary control SINTEF Energy Research has developed a method, called *Stepwise Power Flow (SPF)* [Bakken et al 2005 a]. The basic methodology of Stepwise Power Flow was developed in the Statnett project ”Operational Security and Control” [Bakken et al 2005 b], using the MatPower toolbox [Zimmerman & Gan 1997] for MATLAB. In the context of the WILMAR project the Stepwise Power Flow routine has been further developed to take into account wind power variations, and to in one simulation, simulate the two synchronous systems in the Northern-European system connected through HVDC-links.

The main idea with the Stepwise Power Flow method is to use a sequence of stationary power flow analyses to capture slow system dynamics in the minutes range from stationary droop response through fast reserves (Balancing Power from Balancing Market) to scheduled generation changes, while transient dynamics are neglected. Regular power flow calculations assume balance between scheduled generation and actual load, but this is formally correct only once or a few times during the hour in a real power system where the load is dynamically changing. With two power flow situations imported from the Wilmar Planning tool converted into PSS/E (one situation is the power flow in the beginning of the simulated hour and the other is the power flow at the end of the simulated hour), a sequence of modified power flow analyses are executed in a defined number of steps between the basic cases. In the present version the system load is assumed to change linearly through the hour (the Wilmar Planning tool assumes no stochastic load changes), while scheduled generation is changed only at the change of hour (the instant of change of the hour is user defined). Wind power production may be changed as the user defines it every time step (for instance every fifth minute) of the simulation. Figure 4 illustrates how it within an hour typically will be a deviation between production and load due to the fact that the scheduled generation does not follow the ramping of the load. The system operator observes the deviation between production and load as a deviation in frequency from 50 Hz.

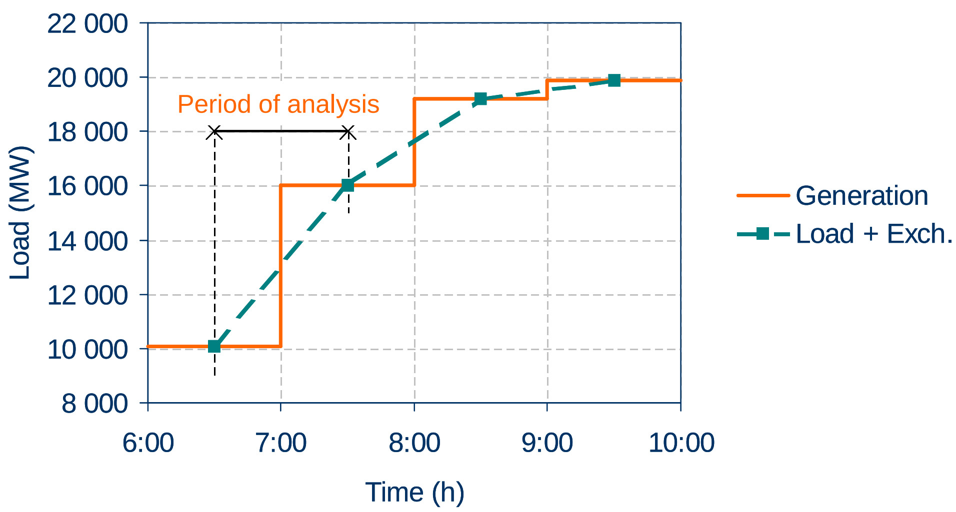


Figure 4 Period of analysis for frequency and power control

In regular power flow analyses the *Swing Bus* generator compensates the imbalance between generation, load and losses. In SPF, this imbalance is for each step shared between all synchronised units according to their droop. The droop of wind power is assumed to be zero which mean that wind power does not contribute to frequency control. This is likely to be a correct assumption due to the unpredictability of wind (the TSO is not likely to accept wind power production for the balancing power market, and the bidder is not likely to reserve wind power for secondary control). The Stepwise Power Flow routine perform a quasi-stationary simulation of

- system frequency
- active power generation and consumption
- spinning reserves and system bias (MW/Hz)
- critical line flows

The inputs to the algorithm are

- power flow and topology data from PSS/E for two consecutive hours
- scheduled generation incl. deviations from schedule
- primary control/unit droop
- wind power production series (modelled as negative load series that are added to the load)
- HVDC ramping

- volume and price of available Balancing Power
- outages (generation, load or lines)
- generator tripping and load shedding

3.1.5 LP optimization with DC power flow

A different approach to model secondary control is developed by KTH in the PhD project "Minimizing Costs for Reserve Power in Integrated Power Systems with Large Amounts of Wind Power". The basic idea is to use an optimization problem formulation to minimize costs for balancing power, and the model is implemented in GAMS [www.gams.com] and MATLAB [www.mathworks.com]. An earlier version of the model was presented in e.g. [Lindgren & Söder 2005], but some modifications have been made for the WILMAR project to make comparisons with SPF possible. The optimisation problem formulation is presented in [Norheim et al 2005].

3.1.6 Extended term dynamic simulation

PSS/E is short for Power System Simulator for Engineering and is manufactured through the Siemens Power Transmission & Distribution, Inc., Power Technologies International (Siemens PTI). SINTEF and VTT have extensive experience in using PSS/E for simulating power system stability.

PSS/E extended term simulation allows users to study longer term effects, such as frequency deviations as affected by prime mover response and voltage changes caused by protective equipment, and yet minimize computer time by providing possibility of changing simulation time step during simulation. The integration method depends on the size of the time step, and therefore smaller time step can be used during and right after large changes/faults, and larger time step at other times. Thus, PSS/E extended term module simulates the mid- to long-term dynamic response of the system.

3.1.7 Conversion program

This section describes how the data from the Wilmar Planning tool are converted to data for the frequency stability studies in WP5. The main task of the data conversion is to generate PSS/E files to WP5 with load flow input data to the 23 generator model for selected hours. The load flow files include data for generation, load, DC transmission and export/import, which are consistent with simulations performed with the Wilmar Planning tool. Besides, a "balancing power list" with bus number, price and volume of the secondary reserves according to JMM simulations is generated for the selected hours. Finally, files with wind power forecast errors for each of the selected hours are generated.

A conversion program "WILMARJMM2PPPE" has been developed to support automatic conversion of the data.

The conversion program uses input from:

- The Wilmar Planning tool input Data Base (IDB), which also provides input data to the Joint Market model and the Long-term model.
- Simulation results with JMM.
- A PSS/E load flow file based on the 23 generator model.

The input from the IDB is:

- A list specifying the JMM region of each PSS/E node.

- A list specifying the JMM region of each JMM unit group.
- A list specifying the unit group and capacities of each JMM unit.

The JMM simulation results input

- Production
- Online capacity (secondary reserve)
- Primary reserves (positive and negative)
- Loads
- Marginal production costs

The output from the data conversion program is:

- PSS/E files for every JMM hour.
- Balancing power lists for every JMM hour.

In the present version, the conversion program generates the PSS/E files with consistent data for load and generation. The data for transmission and export/import has to be written manually into the PSS/E file.

3.1.8 Results from frequency stability cases studies

The frequency stability studies have been carried out with three different tools/methods in order to verify the achieved results, and find potential differences between dynamic simulations and stepwise stationary simulations. Generally the correspondence between the different methods was good.

The frequency stability studies have focused on the ability of the Nordel power system to maintain frequency control within the specified requirements during normal operation. Only control problems related to under-frequency have been considered, i.e. the requirements for the Nordel system states that the frequency during normal operation should be higher than 49.9 Hz. The reason for this is that no major technical problems are expected related to over-frequency. Wind turbines can be stopped or wind farm output can be reduced effectively to deal with generation surplus. It has also been investigated if the power flow between different regions in the Northern European system (Nordel plus West Denmark and North-West Germany) are acceptable. The case studies are chosen based on simulations performed with the Wilmar Planning tool developed in WP6. The output from the JMM in terms of production, load, wind power, etc. for two consecutive hours of interest are used as input to the frequency stability simulations. The WP5 analyses simulate in more detail the variation in flow, production, load, and system frequency within the hour between the two consecutive instances given from WP6. This way the WP5 simulation may reveal overloads, unacceptable frequency deviations, or lack of balancing power.

A 2001 case served as a test case to verify the simulation methods applied to simulate frequency stability. These methods included activation of power on the balancing power market. Together with the simulated 2010 cases the analysis illustrates potential problems that can be revealed with the frequency stability studies, but not with the Wilmar Planning tool.

One possible problem in the analyses was related to the different network representation in the Wilmar Planning tool and in the frequency stability simulations.

Due to including the network impedances the power flow was not determined by the transmission limits as in the Wilmar Planning tool simulations, but by the physical properties of the grid. This way the flow deviated from the Wilmar Planning tool simulations and in some cases transmissions between regions became overloaded.

One solution to this is to include network impedances in the Wilmar Planning tool in order to reveal potential overloads. This would not guarantee that the overloads are avoided within the hour and still the WP5 type analysis would be useful. However, it will decrease the probability for heavy overload and one can argue that potentially overloads anyway could be treated by moderate trading on the balancing power market.

The main conclusions from the case studies are summarized below:

- Location of balancing power: In the 2010 case with high wind power production (10% wind case) the location of balancing power enhanced the overload of a certain transmission corridor. This illustrates the importance of not only having enough reserves, but also that the location of the reserves can become increasingly critical.
- Drop of system frequency to unacceptable levels: This is always to some extent possible in the present day system, as it is the transmission system operator that manually activates bids on the balancing power market to avoid unacceptable system frequencies during normal operation. In one of the 2010 cases the Stepwise Power Flow simulations showed that that balancing power could not be activated fast enough to keep the frequency above 49.9 Hz. Nevertheless, the amount of balancing power activated during a simulated hour was always well below 50 % of the 4400 MW requirement for balancing power in the Nordel system (if West Denmark is disregarded).

Solutions to the observed problems and recommendations regarding integration measures are either related to improvements in technical control, new market arrangements or network reinforcements:

- Continue to develop market based solutions that enable demand (flexible loads) to take part in power balancing and reserve markets.
- Develop Market based automatic generation control (AGC) as a technical solution to perform faster balancing control.
- Require wind power to take part in the primary control. This increases the cost of wind power, as part of the potential production can not be used. It does, however, increase the system bias and this way the frequency stability.
- Increase requirements for on-line reserves. This will improve frequency stability but is also an expensive solution.
- Enhancing the transmission capacities to reduce local congestions. This means costly investments and is often a long process.

3.1.9 Transient stability studies

In the transient stability analysis one case study has been performed on how a new 198 MW offshore wind power park wind farm planned in Eastern Denmark would influence the Nordel transmission system after a transient fault close to the new wind farm. The impact of the transient fault on the wind farm itself was also studied. The work has been submitted for publication in Electrical Power Systems Research [Clemens et al 2005].

Characteristic for the Nordic power system is that it is geographically large, but at the same time it is of comparably small capacity, due to Norway, Sweden, Denmark and Finland being only sparsely populated countries. This makes it more vulnerable to high levels of wind power penetration if the installed turbines are uncontrolled distributed generators.

Until recently wind turbines connected to the Nordic power system were not engaged in the control and support of the system. If transient faults in the system lead to considerable excursions in voltage and/or frequency the wind turbines were to disconnect and to reconnect only once the system has returned to stable operation. Increasing wind power penetration leads to the problem that considerable amount of generation might disconnect in case of a transient fault in the system, causing the system to become unstable from an otherwise harmless fault situation. To prevent such situations newly installed wind turbines in Denmark have to comply with grid connection requirements that demand wind turbines to ride through transient faults [Elkraft System & Eltra 2004 a; Elkraft System & Eltra 2004 b].

The model of the Nordic power system used in these investigations is the 23 generator model described in section 3.1.2. For the transient stability study, the dynamic version of the 23 generators model is applied, including speed governors and voltage control of the generators. SINTEF originally developed the 23 generators model in the power system simulation software PSS/E. For the present transient stability study, the model has been converted to the power system simulation tool Power Factory from DIgSILENT [www.digsilent.de]. The possibility to examine if the power flow and dynamic responses was preserved in this process and the fact that the project partner Risø needed the DIgSILENT format in order to perform the transient stability studies were the motivation for performing the conversion. It turned out to be a not straight forward process, but eventually a good correspondence between the PSS/E model and the DIgSILENT model was obtained.

At Risø National Laboratory a model of the wind power connected to the Nordic power system in eastern Denmark was added to SINTEF's Nordic power system model. This additional model has been developed in cooperation with the Danish transmission system operator.

In the transient stability studies it was considered how a future 198 MW offshore wind farm in Eastern-Denmark would influence the post-fault conditions in the Nordel system, in the case of a 100 ms symmetrical three phase short circuit in Eastern-Denmark (not far from the new offshore wind farm). It was also tested if a grid frequency controller in the future 198 MW wind farm could improve the post-fault conditions in the Nordel system. The main finding can be summarized as:

- The simulations shows that the future offshore wind farm will cause increased stress on the voltage locally in South-East Denmark.
- It will also upset the grid frequency, as it causes strong rotor speed oscillations in the synchronous generator modelling East-Denmark (these oscillations are observed throughout the Nordel system).
- The grid frequency controller in the new wind farm at Nysted will give positive damping of these oscillations, and improve the voltage response at Nysted after the fault has been disconnected.

3.1.10 Small signal stability

The work described in the present section has been published both on the Nordic Wind Power Conference 2004 [Hagstrøm et al 2004] and with an improved version in the Wind Energy Journal July-September 2005 [Hagstrøm et al 2005].

Integrating a large amount of wind power in the Nordel system will influence the oscillation modes in the system. In the context of considering the whole system it is the inter-area oscillation modes that were seen as most interesting for the WP5 work. Simulations on how different technologies influenced the damping of the inter-area oscillation modes were performed in the PSS/E.

The transient and small signal stability analyses have been performed independent of specific WP6 cases and are of more principle character. However, one still uses the simplified model of the Nordel system as basis for the studies analysed.

The impact on the inter-area mode oscillations with wind power integrated into the grid is not yet well explored. It is therefore interesting to simulate the Nordic grid with large scale wind power integration, and investigate how the wind power will influence the inter-area mode in the Nordic grid. Inter-area mode oscillation can be defined as the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties. The natural frequency of these oscillations is typically in the range of 0.1 to 1 Hz. In the Nordel system the two most influencing inter-area mode is the 0.30 Hz oscillation mode that is well observable in the power flowing in the AC-connections between Sweden and Finland and the 0.58 Hz mode that is observable in the power flowing in the lines between Southern-Norway and Sweden in the so called Hasle-corridor.

The oscillations were excited trough different disturbances. The 23 generator model was used to model the Nordel grid plus Germany and Jutland. The initial power flow for all dynamic simulation was a typical cold fall day situation (16300 MW production in Norway and 50400 MW production in the Nordel system). Two places are chosen to observe the inter-area mode oscillations. One is the Hasle-corridor between southern Norway and Sweden, the other is the AC-connection between Finland and Sweden in the north.

Only cases with wind power integration in Norway have been studied. It is however expected that this made the results easier to interpret and that it was a good approach for making principle studies on how large-scale wind power integration may affect the Nordel system.

Case 1

Case 1 is the reference model, and is without wind power production in Norway. For this model the production in Norway is 16.300 MW and 50.400 MW in the Nordic interconnection. This production is a medium production situation, i.e. it corresponds to the production of a cold autumn day.

Case 2

In Case 2, 1.000 MW of wind power is implemented in the middle of Norway. This power replaces 1.000 MW of hydropower from the same area. Accordingly, the model is equal to the one in Case 1, but wind power is implemented into the Norwegian grid. Three different generator types are simulated, squirrel cage induction machine, SCIM, doubly fed induction machine, DFIG, and direct drive synchronous generator, DDSG. There is no wind model implemented into the wind power plant, i.e. the generators are simulated with constant mechanical torque.

Case 3

In Case 3, 5.000 MW of wind power is implemented into the grid. 1.800 MW is implemented at the western coast of southern-Norway, 1.000 MW is implemented in the middle of Norway and 2.200 MW is implemented in the northern part of Norway. The wind power replaces hydropower at each node in the same manner as described in Case 2. As in Case 2, three different generator types are simulated, SCIM, DFIG and DDSG. Also as in Case 2, there is no wind model implemented into the wind power plant, i.e. the generators are simulated with constant mechanical torque.

The simulations showed that it is only the oscillation mode between Norway and Sweden that is influenced to a significant degree from large-scale wind power integration in Norway. The reason for that the inter-area oscillation mode between Finland and Sweden is not influenced by large scale wind power integration in Norway is simply because the 0.3 Hz mode is not influenced by the generators in Norway.

The simulations indicate that the different wind power technologies will influence the damping of the 0.58 Hz mode differently. Basically, wind turbines with the traditional squirrel cage induction generators will improve the damping of this mode, while wind turbines with the doubly fed induction generators or full frequency converters will decrease the damping of the 0.58 Hz mode. The worst impact on damping of the 0.58 Hz mode is from wind turbines with the direct drive synchronous generators and frequency converters. In this case the damping of the 0.58 Hz mode is decreased from 6.6 % in the case without wind power in Norway to 3.8 % in the case with 5000 MW of wind turbines in Norway.

It is important to keep in mind that wind turbines can be controlled in different ways, and that the power and speed control strategies of the wind turbines may influence the system damping. However, large-scale wind power integration will influence the system damping, and the influence might be significant unless the power control systems are designed to provide damping.

There exist well known solutions to damp inter-area oscillation modes, referred to as power system stabilisers. Power system stabilisers are usually designed as low cost auxiliary control loops, which can be realised as an extra control loop in the excitation system of a generator, a FACTS device like SVC, or a HVDC-link.

3.2 Wilmar Planning tool

Section 1 gives an overview of the Wilmar Planning tool.

3.2.1 Design of Joint Market model

The Joint Market model is documented in detail in (Meibom et al 2006). The structure of the power markets in Germany and the Nordic countries were presented in Wilmar deliverable 3.2. (Meibom et al 2004) along with a first outline of the design of the Wilmar Planning tool.

The integration of substantial amounts of wind power in a liberalized electricity system will impact both the technical operation of the electricity system and the electricity market. In order to cope with the fluctuations and the partial unpredictability in the wind power production, other units in the power system have to be operated more flexibly to maintain the stability of the power system. Technically this means that larger amounts of wind power will require increased capacities of spinning and non-spinning power reserves and an increased use of these reserves. Moreover, if wind power is concentrated in certain regions, increased wind power generation may lead to bottlenecks in the transmission networks. Economically, these changes in system operation have certainly cost and consequently price implications. Moreover they may also impact the functioning and the efficiency of certain market designs. Even if the wind power production is not bided into the spot market, the feed-in of the wind power will affect the spot market prices, since it influences the balance of demand and supply.

As substantial amounts of wind power will require increased reserves, the prices on the regulating power markets are furthermore expected to increase. Yet this is not primarily due to the fluctuations of wind power itself but rather due to the partial unpredictability of wind power. If wind power were fluctuating but perfectly predictable, the conventional power plants would have to operate also in a more variable way, but this operation could be scheduled on a day-ahead basis and settled on conventional day-ahead spot markets. It is the unpredictability of wind power which requires an increased use of reserves with corresponding price implications.

In order to analyse adequately the market impacts of wind power it is therefore essential to model explicitly the stochastic behaviour of wind generation and to take the forecast errors into account. In an ideal, efficient market setting, all power plant operators will take into account the prediction uncertainty when deciding on the unit commitment and dispatch. This will lead to changes in the power plant operation compared to an operation scheduling based on deterministic expectations, since the cost functions for power production are usually non-linear and not separable in time. E.g. even without fluctuating wind power, start-up costs and reduced part-load efficiency lead to a trade-off for power plant operation in low demand situations, i.e. notably during the night. Either the power plant operator chooses to shut down some power plants during the night to save fuel costs while operating the remaining plants at full output and hence optimal efficiency. Or he operates a larger number of power plants at part load in order to avoid start-up costs in the next morning. This trade-off is modified if the next increase in demand is not known with (almost) certainty. So in an ideal world, where information is gathered and processed at no cost, power plant operators will anticipate possible future wind developments and adjust their power plant operation accordingly. The model presented in the following describes such an ideal and efficient market operation by using a stochastic linear programming model, which depicts 'real world optimization' on the power market on an hourly basis with rolling planning. With efficient markets, i.e. also without market power, the market results will correspond to the outcomes of a system-wide optimization as described in the following. The cost and price effects derived for the integration of wind energy in this model should then provide a lower bound to the magnitude of these effects in the real, imperfect world.

In a liberalized market environment it is possible not only to change the unit commitment and dispatch, but even to trade electricity at different markets. The Joint Market model analyses power markets based on an hourly description of generation, transmission and demand, combining the technical and economical aspects, and it derives hourly electricity market prices from marginal system operation costs. This is done on the basis of an optimisation of the unit commitment and dispatch taking into account the trading activities of the different actors on the considered energy markets. In this model four electricity markets and one market for heat are included:

1. A day-ahead market for physical delivery of electricity where the Nord Pool market is taken as the starting point. This market is cleared at 12 o'clock for the following day and is called the day-ahead market. The nominal electricity demand is given exogenously.

2. An intra-day market for handling deviations between expected production agreed upon the day-ahead market and the realized values of production in the actual operation hour. Regulating power can be traded up to one hour before delivery. In the present version of the Joint Market model the demand for regulating power is only caused 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.

4. An intra-day market for positive secondary reserve power (minute reserve) mainly to meet the N-1 criterion and to cover the most extreme wind power forecast scenarios that are neglected by the scenario reduction process. Hence, the demand for this market is given exogenously to the model.

5. Due to the interactions of CHP plants with the day-ahead and the intra-day market, intra-day markets for district heating and process heat are also included in the model. Thereby the heat demand is given exogenously.

The model is defined as a stochastic linear programming model (Birge and Louveaux, 2000), (Kall and Wallace, 1994). The stochastic part is presented by a scenario tree for possible wind power generation forecasts for the individual hours. The technical consequences of the consideration of the stochastic behaviour of the wind power generation is the partitioning of the decision variables for power output, for the transmitted power and for the loading of electricity and heat storages: one part describes the different quantities at the day-ahead market (thus they are fixed and do not vary for different scenarios). The other part describes contributions at the intra-day-market both for up- and down-regulation. The latter consequently depends on the scenarios. So for the power output of the unit group i at time t in scenario s we find $P_{i,s,t} = P_{i,t}^{DAY\_AHEAD} + P_{i,s,t}^{+} - P_{i,s,t}^{-}$. The variable $P_{i,t}^{DAY\_AHEAD}$ denotes the energy sold at the day-ahead market and has to be fixed the day before. $P_{i,s,t}^{+}$ and $P_{i,s,t}^{-}$ denote the positive and negative contributions to the intra-day market. Analogously the decision variables for the transmitted power and the loading of electricity and heat storages are defined accordingly.

Further the model is defined as a multi-regional model. Each country is sub-divided into different regions, and the regions are further sub-divided into different areas. Thus, regional concentrations of installed wind power capacity, regions with comparable low demand and occurring bottlenecks between the model regions can be considered. The subdivision into areas allows separate district heating grids within regions.

3.2.1.1 Rolling Planning

It is not possible and reasonable to cover the whole simulated time period of for instance two weeks with only one single scenario tree. Therefore the model uses the multi-stage recursion approach with rolling planning (Buchanan et al 2001). In stochastic multi-stage recourse models, there exist two types of decisions: decisions that have to be taken immediately and decisions that can be postponed. The first kind of decisions are called "root decisions", as they have to be decided "here and now" and before the uncertain future is known. The second kind of decisions is called "recourse decisions". They are taken after some of the uncertain parameters are known. These "recourse decisions" can start actions which might possibly revise the first decisions. In the case of a power system with wind power, the power generators have to decide on the amount of electricity they want to sell at the day-ahead market before the precise wind power production is known (root decision). In most European countries this decision has to be taken at least 12-36 hours before the delivery period. And as the wind power prediction is not very accurate, recourse actions are necessary in most cases when the delivery period is in the near future and the wind power forecast becomes more and more accurate (recourse decisions).

In general, new information arrives on a continuous basis and provides updated information about wind power production and forecasts, the operational status of other production and storage units, the operational status of the transmission grid, heat and electricity demand and updated information about day-ahead and regulating power market prices. Hence, an hourly basis for updating information would be most adequate. However, 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 scenario tree with a total of $s = n^{mk}$ scenarios (assuming that scenario reduction techniques are not applied). It is therefore necessary to simplify the information arrival and decision structure in a stochastic model. Hence, the model steps forward in time using rolling planning with a 3 hour step holding the individual hours. This decision structure is illustrated in **Error! Reference source not found.** showing the scenario tree for four planning periods covering half a day. For each planning period a three-stage, stochastic optimisation problem is solved having a deterministic first stage covering 3 hours, a stochastic second stage with five scenarios covering 3 hours, and a stochastic third stage with 10 scenarios covering a variable number of hours according to the rolling planning period in question (in this way the determination of the shadow values is eased). In the planning period 1 the amount of power sold or bought from the day-ahead market is determined. In the subsequent replanning periods the variables standing for the amounts of power sold or bought on the day-ahead market are fixed to the values found in planning period 1, such that the obligations on the day-ahead market are taken into account when the optimisation of the intra-day trading takes place.

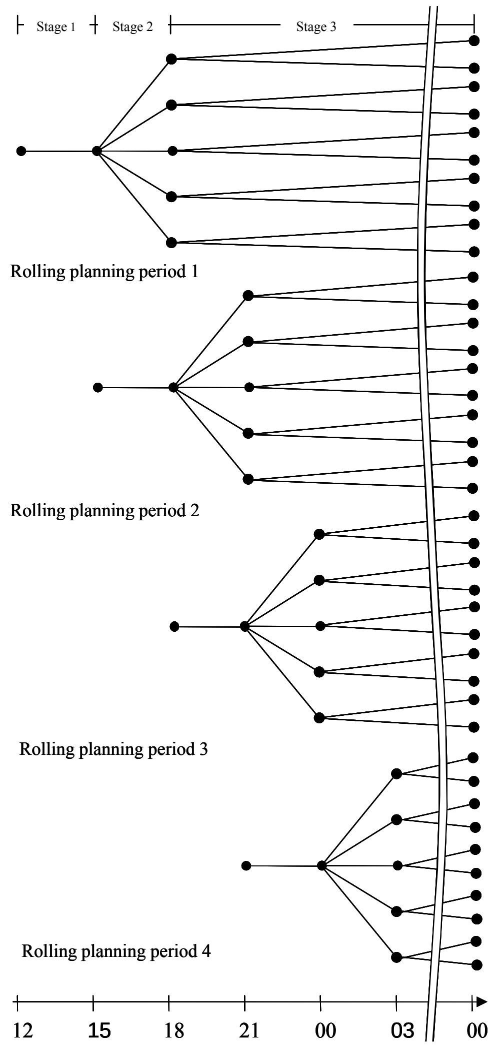


Figure 5 Illustration of the rolling planning and the decision structure in each planning period within half a day.

3.2.1.2 Scenario creation and scenario reduction

The inclusion of the uncertainty about the future wind power production in the optimisation model is considered by using a scenario tree. The scenario tree represents wind power production forecasts with different forecast horizons corresponding to each hour in the optimisation period. For a given forecast horizon the scenarios of wind power production forecasts in the scenario tree is represented as a number of wind power production outcomes with associated probabilities, i.e. as a discrete distribution of future wind power production levels. The construction of this scenario tree is carried out in two steps:

A. Modelling of the wind speed forecast error and the simulation of the distributed wind power forecast scenarios, whose first values of the root node are identical.

B. Reduction of the wind power forecast scenarios to the scenario tree with three stages.

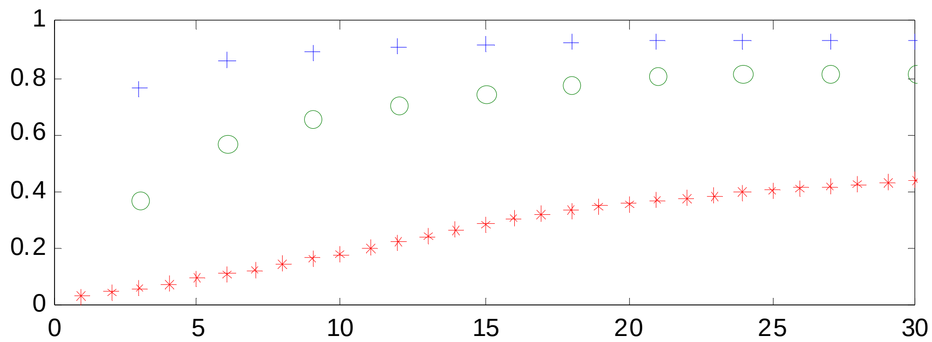
In the following these steps are described in more detail.

Modelling the wind power forecast data process

The generation of wind power forecast scenarios is based on time-series of measured wind speed and of historical forecast errors of wind speed predictions. The increasing trend of the wind speed forecast error with rising forecast horizon is reproduced using multidimensional Auto Regressive Moving Average (ARMA) time-series:

$$X_{WF}(k) = \alpha_{WF} X_{WF}(k-1) + Z_{WF}(k) + \beta_{WF} Z_{WF}(k-1) \tag{1}$$

where $X_{WF}(k)$ is the wind speed error and $Z_{WF}(k)$ is the random variable with given standard deviation in the forecast hour k for the wind power farm WF ($X_{WF}(0) = 0$ and $Z_{WF}(0) = 0$, given α_{WF} and β_{WF}). The random variables $Z_{WF}(k)$ are normally distributed and created by Monte Carlo simulations resulting in a predefined large number of scenarios of the wind speed forecast error. Thereby the correlation between the forecast errors at spatial distributed wind power farms is considered following the approach of (Söder, 2004). For example, data analysis from Sweden (Figure 5) shows that the closer the stations, the higher are the correlations between forecast errors and that the correlation between different stations increases with forecast lengths.



+ Maglarp – Bösarp (15 km) O Maglarp – Sturup (26 km) + Näsudden – Ringhals (370 km)

Figure 5 Correlation between forecast errors for different pairs of stations (Söder 2004).

In order to derive the wind power forecast from the wind speed forecast for each region, technological aspects of the wind power stations located in the considered region are needed. Additionally, their spatial distribution within each region has to be taken into account. This yields an aggregation of the power generation in each region by smoothing the power curves (Figure 6).

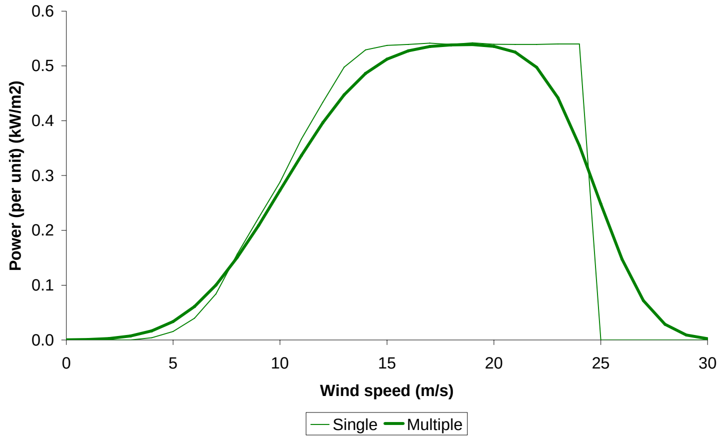


Figure 6 A standard normalised power curve ('Single') and the corresponding smoothed power curve ('Multiple'). Source: (Norgard et al. 2004).

Scenario reduction

In order to keep computation times small for models representing a trans-national market with a huge number of generating units, only significantly less scenarios than the scenarios created before by the Monte Carlo simulations can be used. Simply generating a very small number of scenarios by Monte Carlo simulations is not wanted since less scenarios cannot represent the distribution of wind speed forecast errors adequately. Hence, the aim is to loose only a minimum of information by the reduction process applied to the whole set of scenarios. As the current version of the scenario reduction algorithm reduces the standard deviation of the original generated scenarios, the most extreme wind power forecast scenarios have to be considered by the non-spinning secondary reserve power market.

Two steps are necessary for the scenario reduction: first, the pure number of scenarios has to be reduced. Afterwards, based on the remaining scenarios that still form a one-stage tree, a multi-stage scenario tree is constructed by deleting inner nodes and creating branching within the scenario tree. Therefore a stepwise backward scenario reduction algorithm based on the approach of (Dupacova et al. 2003) is used: the original scenario tree is modified through bundling similar scenarios or part of scenarios. Bundling two scenarios or parts of scenarios means deleting the one (or the part of the scenario) with the lower probability and adding its probabilities to the remaining one (Figure 7). As a measure for the similarity of different scenarios, the Kantorovich distance between two scenarios is used.

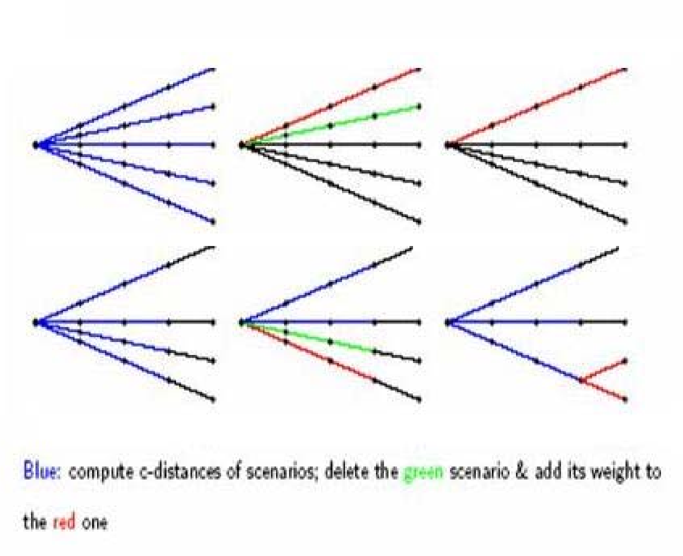


Figure 7 Example for the backward scenario reduction heuristic. Source: modified figure from (Gröwe-Kuska et al., 2001)

The scenario creation and reduction is carried out with different modules that are implemented in Matlab® to the so called Scenario Tree Tool. The Scenario Tree Tool is documented in (Barth et al. 2005; Norgaard et al. 2004). An overview of the different modules and the data flow can be found in Figure 8.

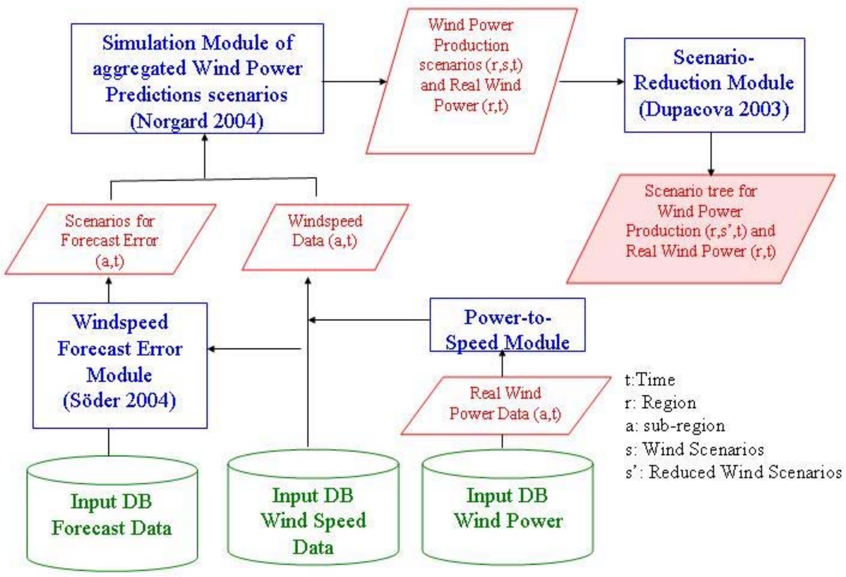


Figure 8 Data flow of the sub-modules of the Scenario Tree Tool.

3.2.2 Design of Long-term model

The design of the Long-term model is documented in (Ravn 2006).

The analysis of wind power emphasises the stochastic behaviour of wind generation and forecast errors; these aspects are mainly of a short term nature (i.e., related to hours or at most a few days ahead). However, in order to operate the system efficiently "now", it is necessary to incorporate mechanisms that secure that operation “now” is balanced against operation “later”. This is relevant for the operation of hydro power with reservoirs. In the Northern European context there are hydro reservoirs that are designed for holding water throughout a year or more, and with a relative size of energy and power that give them a significant influence on the electricity system in the region. Moreover, due to the relatively large short term flexibility of hydro power production from reservoir, this is particularly interesting in relation to fluctuating energy sources like wind power.

The purpose of the LTM is to provide the necessary framework in relation to hydro power reservoirs for making decisions at any time in the Joint Market Model (JMM) that are balanced against JMM decisions later. This is done by providing water values, i.e., an evaluation of the value of hydro power from reservoirs. In the JMM, these water values are used as marginal cost for the use of hydro power from reservoirs.

3.2.2.1 Main idea and function

Water values represent the value (expressed in monetary terms, such as Euro/MWh) of hydro power from reservoirs (in the following called HYRS). HYRS is for the present purpose characterised by three things. First, that the marginal cost of operation is small compared to the average marginal cost in the system under consideration; second, that the energy can be stored on a long terms scale (e.g., one year)); and third, that the energy is limited on a long terms scale (again e.g., one year), although the quantity is stochastic.

The consequence of this is that the value of one MWh additionally of water will be mainly determined by where it can best be used. This will be as a substitute of one MWh of alternative production, which typically will be thermal. So, paradoxically, the value of hydro power can not be determined independently of thermal power. By extending such reasoning it follows that the water value can only be determined by considering the whole system – both in the geographical extension (because any region with HYRS is connected with the other regions through electricity transmission) and in the time extension (because the long term operation consists of a large number of short term operations).

Ideally then, the JMM and the LTM should be solved simultaneously. This is practically impossible due to the size of the problem, and the separation of the whole problem into two models, the JMM and the LTM, is the response to this.

The LTM operates on a simplified version of the whole problem. The simplifications have been done such that the emphasis on the resulting model is the long terms aspects related to operation of HYRS. In particular:

- Combined heat and power (CHP) is represented by equivalent hourly electricity production.
- No aspects of unit commitment or ramping limitations for thermal power plants are represented.
- Wind power is represented by one hourly time series covering one year (i.e., deterministic).

In all other aspects the data that is common between the LTM and the JMM is identical.

In addition to the data entering the JMM, the LTM receives a time series for hydro inflow to reservoirs. This time series is given on a weekly basis, covering a number of historical years (presently 1980 – 2002). Thus, it is in its origin similar to the time series for unregulated hydro inflow (which enters both the JMM and the LTM, and which is on an hourly basis). These time series are taken as representative of the stochastics of hydro inflow.

The LTM basically operates on a weekly basis, corresponding to the available time series for hydro inflow to reservoirs. However, the variation between the individual hours is represented to some extent, such that the variation in load, forced electricity production (from CHP, wind and unregulated hydro power), marginal electricity costs and exploitation of transmission links are taken into account.

The WILMAR model is a multi-regional model, where a region is characterised by having unlimited electricity transmission capacity internally. Between regions there are transmission possibilities with technical specifications in terms of capacities and costs. Thus, regional differences with respect to HYRS, concentrations of installed wind power, demand and occurring bottlenecks between regions can be considered. This motivates that also the LTM is multiregional.

A classical approach to determining water values uses dynamic programming. This technique permits representation of the technical constraints in the system and exactly reflects the sequential decision structure of the problem. Moreover, it permits handling of stochastic elements (in this case, the hydro inflow), and calculation of water values as expected values.

The weakness of dynamic programming is that, except for special situations (notable the linear-quadratic case) its practical application is dependent on the dimension of the state space (in the LTM context: the number of reservoirs) not being too large (typically meaning not more than two or three).

The dynamic programming approach has therefore been implemented such that it operates on a one reservoir model. This is obtained by aggregating all regions into one region (and hence also only one reservoir).

To represent multiple reservoirs a second approach has been developed. This is based on suboptimal and adaptive control ideas (Bertsekas 1987) with various adaptations to the problem at hand. The approach uses a certainty equivalent control where the idea may be described as follows.

The available data is mainly that previously described, given as deterministic values: the production system with costs and capacities; electricity demand; forced electricity production (primarily from CHP, wind). Further there are time series for hydro inflow for a number of years. For these time series their mean value time series are calculated, i.e., for hydro with reservoir a time series with weekly values for each reservoir is given, for unregulated hydro a time series with hourly values for each region is given

Assume that at the beginning of week *w* the following is available: the present hydro reservoir filling and the nominal (i.e., required according to model philosophy, see below) reservoir filling one year ahead. Then formulate and solve the problem consisting in minimising the operations cost over one year, starting in week w, using mean value time series for hydro. The model (called LTM2) may have an approximate representation of the hours of the year (e.g., 1000 hours), while the reservoir filling has a weekly representation. The solution to this problem specifies, among other things, how much regulated hydro power to use during week w.

At the beginning of the following week it is possible to calculate the filling of the hydro reservoir from the calculated use of regulated hydro power and the inflow (which may be taken from a specific historical year, or draw at random from a probability distribution corresponding to the historical values, according to the assumptions taken in the JMM).

The above model, which is a typical example of a rolling horizon idea, uses a fixed end point for reservoir filling, the nominal value. This secures that the reservoirs are not emptied, but kept at sustainable, yet time varying, levels The nominal trajectory for reservoir filling is found as follows. Formulate and solve the problem that minimises the operations cost over one year, while using mean value time series for hydro, and requiring a cyclical relation over time (i.e., the reservoir filling at the end of the year must be the same as at the beginning of the year). The model (called LTM1) has the same representation of time as the LTM2 model described above.

Obviously the use of regulated hydro power may deviate from the solution found as described, for instance if wind power deviates much from the assumed value. This is taken care of in the JMM, which handles the time perspective within the week.

The interplay between the LTM and the JMM may then be described as follows:

1. Solve LTM1 to get nominal trajectories for reservoir filling.
2. Select the initial week and initial reservoir filling, pass this information to LTM2.
3. Solve LTM2 to obtain water values, pass water values for the present week to JMM.
4. Solve JMM over one week, using the received water values as marginal costs for use of regulated hydro power.
5. In JMM, calculate the reservoir filling at the beginning of the next week, pass the next week's number and initial reservoir filling to LTM2 and go to step 3.

Various refinements are possible. In particular, the JMM may call LTM2 more frequently than weekly in order to permit timely update of water values.

A special issue concerns the possible systematic deviation between the price levels in JMM and LTM. As explained, the LTM relies on a simplified representation of the energy system, compared to the JMM. Some of the simplifications might lead to lower prices in the LTM, in particular the omission of unit commitment, ramping constraints and wind power stochastics. On the other hand, some simplifications might lead to higher prices in the LTM, for instance because by converting the CHP production technologies to electricity only technologies some dispatch possibilities related to use of heat storage are missed. For this reason a calibration possibility is built into the interplay between the JMM and LTM models.

3.2.3 Collection of input data

A lot of data is needed when making a model of the power systems in Denmark, Finland, Germany, Norway and Sweden. Many of the data is linked to the geographical representations used in the model. The geographical representations covered are countries, regions and areas. Table 1 gives an overview of the data needs in Wilmar.

Data Object	Scope
Hourly regional time series: - Electricity demand - Exchange with third countries - Wind power production	 Year 2000-2002 Year 2000-2002 Year 2000-2002
Daily regional time series: - Uncontrollable hydro inflow Finland and Germany - Controllable hydro inflow Finland and Germany	 Year 1980-2002 Year 1980-2002
Weekly regional time series: - Controllable inflow Norway and Sweden - Uncontrollable inflow Norway and Sweden	 Year 1980-2002 Year 1980-2002
Hourly area-dependent time series. - Heat demand	 Year 2000-2002
Yearly time series (projections) - Fuel prices - Yearly heat demand - Yearly electricity demand - Yearly exchange with third countries	
Technology data (capacities, technical and economic characteristics): - Existing units (production, transmission and storage) - Future units	
Tariffs: - Power transmission and distribution - Heat distribution	
Taxes: - Fuel taxes, taxes on the use of electricity to electrical heating	
Emission policies: - Tradable emission permit prices (CO_2, SO_2)	
Power demand price elasticities	

Table 1 Overview of the data needs in the Joint Market model.

The data set in Wilmar ended up with being of quite good quality. The collected wind and hydro data is described in Wilmar deliverable 2.1 (Nørgård et al 2004). Wilmar deliverable 3.1. describes other data input to the Wilmar Planning tool.

3.2.4 Storage of input data

The purpose of the Planning tool input database is to (1) store technology data, time series data, and geographical data as well as to (2) select the subset of the total data that is needed as input in a specific Joint Market model (JMM) simulation or Long term model (LTM) simulation and (3) convert this 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 and include the values specified in the files in the Joint Market Model simulation, or alternatively a series of text files such that the LTM can read the files. The design of the Planning tool input database reflects the data needs for the JMM and LTM, and the level of detail used in the model for the description of the Northern European power (and heat) system.

The design of the Planning tool input database is documented in (Kiviluoma & Meibom 2006), and the visual basic code involved in the database is documented in (Larsen 2006 b).

3.2.5 Design of user shell

The User Shell controls the operation of the Wilmar Planning Tool as shown in Figure 1. In the User Shell various control parameters are set, and then a macro in the Input Database is run that writes input files for the Joint market Model and the Long Term Model. Afterwards these models can be started from the User Shell. Finally, the User Shell can start a macro in the Output Database that imports the output files from the models. In the present version of the Planning Tool the User Shell does not control the Scenario Tree Creation Model that should be run prior to using the rest of the Planning Tool.

A guide to the user shell is available (Larsen 2006 a) as well as a documentation of the visual basic code (Larsen 2006 b).

3.2.6 Design of output database

The Joint Market model output database stores the results of modelling runs and has forms and queries to present the data. It can store several case runs at the same time and has queries for the comparison of different cases. The table structure of the database tries to minimize the size of the database while the query structure tries to minimize the time to retrieve information from the tables. However, when the database holds lot of data, e.g. whole year, some queries will be too slow to use. In these cases it is advisable to use sub-queries and collect the data into Excel sheet for instance.

Basic geographical and time data are linked from the input database. Technology data is imported for each case from JMM, since this data can change from run to run. Variables are recorded at the lowest possible level for each hour, usually at the level of UnitGroups. Recorded variables include production and consumption of electricity and heat, reserve reservations, fuel usage, online status, start ups, and transmission of electricity. Shadow prices of storages as well as marginal prices of the most important equations are also stored.

Most important data can be shown graphically using forms of the database. They utilize the queries that gather the data from the underlying tables. In a form one can choose the object of analysis and the time period for the analysis. There exist forms for electricity prices, wind power forecast vs. realized wind power, power production distributed on fuels, production with consumption and transmission, production from individual UnitGroups, transmission between regions, check for equation balances and a form in which one can compare differences of separate cases.

The design of the Planning tool input database is documented in (Kiviluoma & Meibom 2006)

3.3 Application of the Wilmar Planning tool

Different versions of the Wilmar Planning tool have during the last two years of the project period been applied to analysis of different wind power integration cases. These analyses have been presented at conferences and are being submitted to journals (see Section 3.7).

The analysis has mainly focused on wind power integration issues in a power system covering Germany, Denmark, Finland, Norway and Sweden in year 2010. A base scenario for the development of the power system configuration excluding the development in wind power capacity has been agreed upon among the project partners. The 2010 base power system configuration is a projection of the present power system configuration in Germany and the Nordic countries to 2010 by introducing investments in power plants and transmission lines that are already decided today and scheduled to be online in 2010, and by removing power plants that have been announced to be decommissioned before 2010. Likewise scenarios for fuel prices, electricity and heat demand and the other parameters in the Wilmar Planning tool has been agreed upon. The assumptions are described in (Meibom et al 2006 b).

This 2010 base power system configuration is supplemented by three scenarios for the installed wind power capacity in 2010:

1. A base wind power capacity scenario consisting of a "most likely to happen" projection of wind power capacity according to a review of public information provided by the Wilmar consortium.
2. A 10% wind power capacity scenario consisting of installed wind power capacity in Denmark and Germany corresponding to a "most likely to happen" 2015 projection, i.e. a stronger growth than in the base scenario (equal to cover ca. 11 % and ca. 29 % of the annual electricity demand of Denmark and Germany, respectively) combined with an unrealistic strong growth of wind power capacity in Finland, Norway and Sweden corresponding to installed wind power producing 10% of the electricity consumption in these countries in 2010.
3. A 20% wind power capacity scenario with the same assumption for Denmark and Germany as in the 10% scenario, but a stronger growth in Finland, Norway and Sweden with wind power production covering 20% of electricity consumption in 2010.

The reason for supplementing the base wind scenario with two unrealistic high growth wind power scenarios for especially Finland, Norway and Sweden is that we wanted scenarios where wind power production had a significant effect on the operation of the rest of the power system, and these amounts will most likely not be present in the Nordic power system (except Denmark and Germany) in 2010.

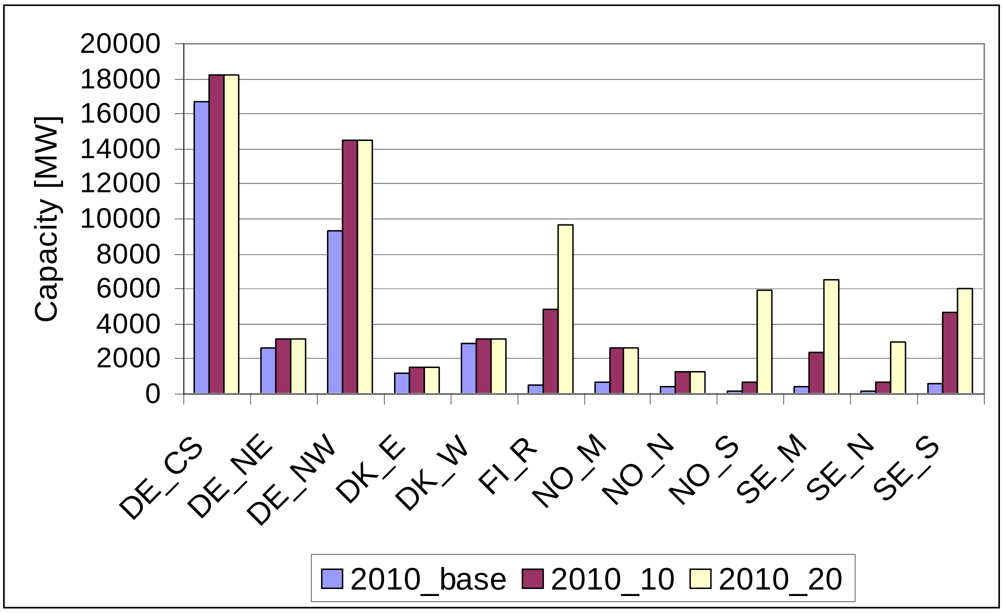


Figure 9 Installed wind power capacity in each region in the three wind power capacity development scenarios.

The three wind power cases have been simulated with the Wilmar Planning tool for a period covering January and February in 2010. In this period the wind power production constitutes 5.8%, 11.8% and 15.6% of the total electricity production for respectively the wind cases: base, 10% and 20%.

Case Name	Change System Costs [MEuro]	Value saved water [MEuro]	Change Windpower Production [TWh]	Avoided costs per MWh extra wind [Euro/MWh]
10%/Base	237.3	163.3 (5.0)	10.8	37.2
20%/Base	335.2	294.5 (9.4)	17.7	35.5
20%/10%	97.9	132.3 (4.4)	7.0	33.0

Table 2 Avoided system operation costs with increasing amounts of wind power production for model runs covering two winter months.

The integration of wind power leads to a reduction of the total system operation costs if investment costs are disregarded, because the wind power production replaces more expensive power production. The total system operation costs consists of the sum of fuel costs, variable operation and maintenance costs, start-up costs, $CO2$ emission costs and taxes and tariffs. By comparing the system operation costs in different wind power cases, the value of different amounts of wind power production in the power system can be evaluated. As increased amounts of wind power production also leads to a decrease in the usage of hydropower, i.e. an increase in the amount of water in hydropower reservoirs, the system costs have to take into account the value of regulated hydropower not used.

Table 2 shows the avoided system operation costs when comparing different wind power cases. Remarkably the avoided costs of wind power production are not reduced very much, when the wind power production is increased, e.g. adding 10.8 TWh wind power production in the 10% case relatively to the base wind case only reduces the avoided costs with 5%. A reduction in the avoided costs are expected, because as more wind power production is added, thermal production with lower and lower marginal production costs will be replaced. This is also the case, if thermal production was added to the power system. The relatively small reduction in avoided costs is due to the simulated period being winter months with a high demand for power, and due to most of the increased wind power production being added in hydropower dominated regions. The production costs of hydropower are mainly determined by the water value, such that the supply curve of regulated hydropower only slightly increases with production levels. The economic value of replacing hydropower production with wind power production is therefore fairly constant over a large interval of hydropower production.

Focusing on the economic consequences for wind power producers when adding more wind power production Table 3 shows the average day-ahead power price achieved by wind power producers and the average penalties paid due to forecast errors, and Table 4 shows the revenue of wind power producers relatively to the penalties paid.

	Average Day-ahead Price [Euro/MWh Wind]	Average Penalty Up regulation [Euro/MWh forecast error]	Average Penalty Down Regulation [Euro/MWh forecast error]
Base	42.5	1.7	1.0
10%	34.8	2.4	3.0
20%	31.7	2.9	2.6

Table 3 Average prices achieved by wind power producers and penalties paid due to wind power forecast errors in a model run covering two winter months.

Table 3 shows that the revenue of wind power producers are reduced significantly when more wind power is added to the power system, mainly due to a reduction in the average day-ahead power price received by wind power producers, but also due to an increase in the average penalty of being in imbalance due to forecast errors. Conventional power producers also experience a reduction in average power prices, but the reduction is less than for the wind power producers, as there still will remain high-price periods when the wind power production is low.

	Revenue DayAhead	Sold Intraday	Bought Intraday	Total Revenue	Up regulation penalty	Down regulation penalty	Penalty/ Revenue
Base	465.4	50.7	76.0	440.1	2.9	1.1	0.9%
10%	758.0	94.1	127.3	724.8	7.7	7.9	2.2%
20%	918.5	124.1	166.3	876.3	13.5	10.0	2.7%

Table 4 Total revenue and penalties paid of wind power producers in the three wind power cases for model runs covering two winter months. All figures in MEuro.

The operational integration costs of wind power production disregarding investments have also been analysed using the three wind power case mentioned above, but running the Wilmar Planning tool for five selected weeks. The five weeks are selected using a scenario reduction technique with the hourly wind power production, electricity demand and heat demand as input parameters, such that the selected weeks are the best representative weeks of a year with regard to the variation in these input parameters. The integration costs have been divided into two groups:

- System operation costs due to forecast errors, which is analysed by comparing the system operations costs in the stochastic simulation with the system costs in a Wilmar Planning tool simulation with perfect foresight, i.e. perfectly predictable wind power production.
- System operation costs due to variability, which is analysed by comparing the system operations costs in the perfect foresight simulation with the system costs in a Wilmar Planning tool simulation with constant wind power production within each week.

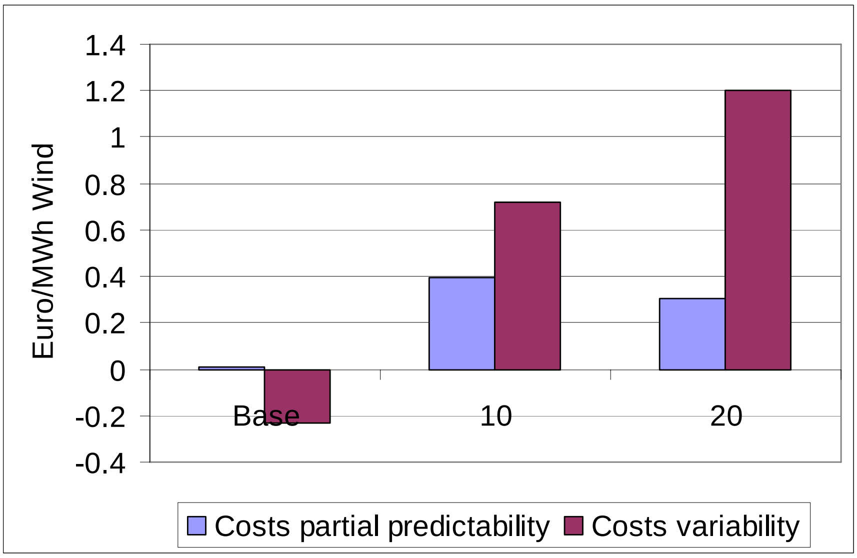


Figure 10 Increase in system operation costs per MWh wind power production when comparing system cost in a model run with constant weekly average wind power production with a perfect foresight model run (Costs variability), and when comparing system costs in a stochastic model run with a perfect foresight run (Costs partial predictability).

Figure 10 shows the results for the three wind power cases. The results are not entirely comparable between the cases due to the uncertainty introduced by only using five selected weeks. Disregarding the base wind case with low and negative integration costs, the results show that the costs of being variable is larger than the costs connected to being partially unpredictable. So the time periods with low loads and large amounts of wind power production generate more costs than the balancing costs. One reason for this is that the regulating hydropower production has very low balancing costs, and that the balancing market modelled is extremely efficient (in effect the perfect balancing market). In reality balancing costs would be higher due to transaction costs and in some cases market power.

Apart from the results presented above, the Wilmar Planning Tool has been used to analyse three types of integrations measures: extension of transmission lines, usage of electricity storages, usage of heat pumps and electrical heating. These analyses have been presented at conferences and are either accepted for publication or have been submitted to journals (see Section 3.7).

3.4 CO2-emission trading and green markets for renewable electricity (WP4)

The aim of the work undertaken in WP4 of the Wilmar project is to analyse the interactions between CO_2 emission trading and markets for electricity produced from renewable energy sources in a liberalised market, including description on how to treat these issues in the Wilmar Planning tool. The work has been documented in Wilmar deliverable D4.1 (Ravn et al. 2004).

The introduction of a common emission-trading system in the EU will have an upward effect on the spot prices at the electricity market. The variations of the spot price imply that some types of power generation may change the situation from earning money to losing money despite the increasing spot price. Heavy restrictions on emissions penalise the fossil-fuelled technologies significantly, and the associated increase in the spot price need not compensate for this. Therefore, a market of tradable emission permits (TEP's) is expected to have a significant influence on the electricity spot price. However, the expected price level of TEP's are met with great uncertainty and a study of a number of economical studies shows a price span between zero and 270 USD per ton of CO_2 depending on the participation or non-participation of countries in the scheme.

As the CO2 emission markets in EU cover more sectors than the power sector, it is not relevant to introduce a CO2 emission market in the Wilmar Planning tool, which only models the power sector. Therefore an exogenously given TEP price has been introduced in the Wilmar Planning tool, such that the variable costs of the power plants include the costs of buying TEPs.

The price-determination at the tradable green certificate (TGC) market is expected to be closely related to the price at the power spot market as the RE-producers of electricity will have expectations to the total price paid for the energy produced, i.e., for the price of electricity at the spot market plus the price per kWh obtained at the green certificate market. In the Wilmar model, the TGC market can either be handled exogenously, i.e., the increase in renewable capacity and an average annual TGC price are determined outside the model, or a simple TGC module is developed, including the long-term supply functions for the most relevant renewable technologies and an overall TGC quota.

The TGC market will only influence the day-ahead market bidding of generating plants using renewable energy sources, i.e., wind power, photovoltaics, waste power and biomass power. Of these technologies, only biomass power has significant short-term marginal generating costs[1]. The reduction in the day-ahead market bidding price due to the existence of a TGC connected to the electricity production will, therefore, probably only have a significant influence on biomass power. It has therefore been decided to include a TGC market only as an exogenously given support to biomass produced power, which makes the biomass power plants more competitive on the power markets.

3.5 Distribution of integration costs (WP7)

The integration of wind power into existing electricity markets entails the so called integration costs. The objective of the work undertaken in WP7 is to identify different treatments to distribute the costs of wind power integration on the individual actors of electricity markets and to derive recommendations for handling the distribution of these integration costs based on an economic analysis.

One important point from the analysis undertaken in WP7 is that wind power integration costs is not a well-defined concept, as the calculation of integration costs always relies on a comparison with an alternative to the wind power production. The determination of this alternative power production is not straight forward, e.g. should increased wind power production be compared with a situation with no increase in wind power production and no other changes, or with a situation with an increase in thermal production equal to the increase in wind, and if so what type of thermal production?

With regard to the distribution of grid connection costs, the analysed country cases of existing practices show similar treatments that allocate the costs to the individual wind power producers. Concerning the costs of necessary grid reinforcements, the shallow

1 The present short-term marginal costs of waste power are very low, because the fuel input (the waste) has a price of zero or below zero (the plants are paid for burning the waste).

connection method dominates the existing treatments. This is contrarily to the WP7 recommendations that favour price-flexible locational signals. However since grid reinforcements have multiple benefits for the operation of electricity grids and for the trading at electricity markets, these costs should be allocated reasonably to several users of the grid.

The structure of the present markets (e. g. using different price models for the regulating power price fixing or different time spans between the closure of the trading activities and the actual delivery hour) as well as how the wind power producers have access to the markets are crucial points when analysing how the distribution of regulating power costs are distributed on actors in different countries. The resulting plurality makes an harmonisation of possible methods for an efficient cost distribution difficult. To provide efficient operational signals to the individual power producers, it has to be ensured at least that the total of the regulating power costs borne by the individual power producers should equal the total costs of the net imbalance.

The WP7 work has been reported in D7.1 (Barth & Weber 2005).

3.6 Recommendations (WP9)

During the work in the WILMAR project recommendations have been identified on how the electricity markets should be organised to enable a cost-effective integration of wind power in large liberalised electricity systems. The main recommendations concern reducing imbalances caused by wind power by bidding closer to delivery hour and aggregating wind power production as well as changing rules for imbalance settlement to make the imbalance charges better reflect the system imbalance costs actually incurred. Also recommendations on improving the use of transmission capacity, making sure that enough regulating power is bid in the markets and enhancing flexible demand and storage participation in markets are suggested. The recommendations are given in D9.1 (Holttinen et al. 2005).

3.7 Overview of journal articles, conference proceedings and master thesis produced in connection with the Wilmar project

Conference proceedings:

Hagstrøm, E, Norheim, I, Uhlen, K: “Large Scale Wind Integration in Norway and Impact on Damping in the Nordic Grid”, Nordic Wind Power Conference, 1-2 March 2004, Chalmers University of Technology

Nørgård, P., Holttinen, H., “A Multi-Turbine Power Curve”, In: Proceedings of Nordic Wind Power Conference NWPC'04, Gothenburg, Sweden, 2004.

Meibom, P., Weber, C., Ravn, H., Söder, L., “Market integration of wind power”, Proceedings European Wind Energy Conference, London, 2004.

Barth, R., Söder, L., Weber, C., Brand, H., Swider, D. “Deliverable 6.2 (b): Documentation WILMAR Scenario Tree Tool, IER, Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart, August 2005, available from www.wilmar.risoe.dk.

Barth, R., Brand, H., Weber, C., “Transmission restrictions and wind power extension - case studies for Germany using stochastic modelling”, Proceedings of the European Wind Energy Conference, London 2004.

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Söder, L., “Simulation of wind speed forecast errors for operation planning of multi-area power systems", Proceedings of the 8th International Conference on Probabilistic Methods Applied to Power Systems, Iowa State University, Ames, Iowa, September 12-16, 2004.

Bakken, B.H, Petterteig, A, Haugan, E, Walther, B, ”Stepwise Power Flow – A new Tool to Analyse Capacity Shortage and Reserve Requirements”, 15th Power Systems Computation Conference, Liege, Belgium, August 2005.

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Journal articles:

Barth, R.; Brand, H.; Swider, D.J.; Weber, C.; Meibom, P., “Regional electricity price differences due to intermittent wind power in Germany – Impact of extended transmission and storage capacities”, Special issue “Integrating intermittent renewable energy technologies, limits to growth?" of the International Journal of Global Energy Issues. Accepted for publication.

Clemens J., Sørensen, P., Norheim, I., Rasmussen, C., “Simulation of the Impact of Wind Power on the Transient Fault Behaviour of the Nordic Power System”, Electrical Power Systems Research; submitted for publication in 2005.

Hagstrøm, E, Norheim, I, Uhlen, K, “Large Scale Wind Integration in Norway and Impact on Damping in the Nordic Grid”, Wind Energy Journal, Vol. 8, NO. 3, July-September 2005.

Holttinen, H, “Hourly wind power variations in the Nordic countries”, Wind Energy Journal, Vol. 8 (2005) No: 2, 173 – 195.

Furthermore several additional conference presentations and journal articles are in preparation.

Master thesis:

Barth, R., “Modellierung des Verhaltens der Windgeschwindigkeit und des deutschen Energiesystems mit hohem Windkraftanteil“, Diplomarbeit, Vol. 391, Institute of Energy Economics and the Rational Use of Energ, University of Stuttgart, Germany, 2003.

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3.8 Assessment of Results and Conclusions

The output of the Wilmar project has been significant. A Wilmar Planning tool covering Denmark, Germany, Finland, Norway and Sweden has been developed, tested and used for analysis of wind power integration issues. The Planning tool has a very high technical state in that the Planning tool has an endogenous treatment of:

- Stochastic wind power production.
- The use of water stored in hydro reservoirs and subject to stochastic water inflow (single reservoir Long-term model).
- Provision of primary and secondary reserves.

To our knowledge no existing electricity system modelling tool except the Wilmar Planning tool handles endogenously both stochastic wind power production and water stored in hydro reservoirs, such that the Wilmar Planning tool has and will in the future contribute significantly to the technical progress within the field of modelling of electricity systems.

Extensive analysis of frequency stability, transient stability and small-signal stability issues have taken place in WP5 of the Wilmar project. Especially the work related to frequency stability involving activation of minute reserves, represents a relatively new approach within the modelling of electricity systems, and therefore has the potential of extending the state-of-the-art within this field. Furthermore the Wilmar project succeeded in making a connection between the Wilmar Planning tool and the WP5 modelling tools, thereby providing a set of tools enabling wind integration studies on many time scales but still building on the same input data.

Analysis of the technical and economic consequences of extending the wind power capacity in a power system covering Denmark, Germany, Finland, Norway and Sweden has been carried out. Interesting results have been obtained that are in the process of being published in journal articles. Still more analysis is needed in order to fully exploit the potentials of the modelling tools developed, and this analysis will take place in future national and trans-national research projects such as the EU funded SUPWIND project.

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4 Acknowledgements

The Wilmar consortium thanks EU for providing financial support to the project.

5 Contact details

Table 5 gives the most recent contact details of the project leaders from each organisation in the Wilmar consortium.

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Table 5 Name and contact details of persons who may be contacted concerning the follow-up of the project.

The organization Elkraft System a.m.b.a. changed name to Energinet.DK from the beginning of 2006.