THESIS ON POWER ENGINEERING, ELECTRICAL
ENGINEERING, MINING ENGINEERING D39

Large-Scale Integration of Wind Energy into the Power System Considering the Uncertainty Information

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The dissertation was accepted for the defence of the degree of Doctor of Philosophy in Power Engineering and Geotechnology on July 2nd, 2009

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Defence of the thesis: September 4, 2009, 14:00, room VII-537 at Tallinn University of Technology, Ehitajate tee 5, Tallinn, Estonia

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for a doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Hannes Agabus ……………….

ISSN 1406-474X
ISBN 978-9985-59-924-2

ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D39

Elektrituulikute integreerimine energiasüsteemi arvestades informatsiooni mittetäielikkust

HANNES AGABUS

ABBREVIATIONS AND UNITS

AC	alternating current
AI	Artificial Intelligence
ANN	Artificial Neural Network
BALTSO	Organization of Baltic Transmission System Operators
CCGT	combined cycle gas turbine
CFBC	circulating fluidized bed combustion
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
DSM	demand side management
EEK	Estonian crown
EU	European Union
EUR	European momentary unit euro
FRT	fault ride trough
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonnes
GW	gigawatt
GWh	gigawatt hour
HVAC	high voltage alternating current
HVDC	high voltage direct current
IPS/UPS	Independent Power Systems and Unified Power system
kV	kilovolt
kW	kilowatt
LP	linear programming
MAE	mean absolute error
MAPE	mean absolute percentage error
MARKAL	long-term energy-environment planning model, abbreviation of "Market Allocation"
max	maximum
min	minimum
MW	megawatt
NORDEL	Nordic Transmission System Operators
Nord Pool	Nordic power exchange
NPP	nuclear power plant
OHL	overhead line
OCGT	open cycle gas turbine
OPGU	optimal planning of generating units
PJ	petajoule
PP	power plant
PSS/E	Power System Simulator for Engineering

RES	renewable energy source
RMSE	root mean square error
SCADA	Supervisory Control And Data Acquisition
SO_2	sulphur dioxide
TPP	thermal power plant
TSO	transmission system operator
TUT	Tallinn University of Technology
TWh	terawatt hour
UCTE	Union for the Coordination of Transmission of Electricity

Conversion factors

1 EUR	15.6466 EEK
1 GWh	3600 GJ

Unit prefixes

k	kilo, 10^3
M	Mega, 10^6
G	Giga, 10^9
T	Tera, 10^{12}
P	Peta, 10^{15}

LIST OF ORIGINAL PAPERS

The present doctoral thesis is mostly based on the following papers, which are referred to in the text by their Roman numerals I-V:

I. **Agabus, H.**, Tammoja, H. Wind Power Production Estimation Through Short-Term Forecast. Oil Shale, Vol. 26, No. 3 Special, pp. 208-219. 2009 Estonian Academy Publishers ISSN 0208-189X.

II. **Agabus, H.**, Palu, I., Tammoja, H. Hiiumaa large-scale offshore wind park integration into Estonian grid. 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. Madrid, Spain 2008: Energynautics GmbH. pp. 498-501.

III. Liik, O., Landsberg, M., Ojangu, J., Kilk, K., **Agabus, H.** Possibilities to develop the use of wind energy in Saaremaa island. Scientific proceedings of Riga Technical University. Serija 4, Power and electrical engineering. 14 (2005) Riga: RTU, 2005. pp. 86-93.

IV. Oidram, R., Landsberg, M., **Agabus, H.**, Attikas, R., Ojangu, J., Palu, I. Problems Related to Grid Connection in Pakri Wind Park. In: Grid Integration and Electrical Systems of Wind Turbines and Wind Farms. Nordic wind power conference, 22-23 May, 2006, Espoo, Finland. Helsinki, Finland: VTT, 2006. (CD-ROM). pp. 1–4.

V. **Agabus, H.**, Landsberg, M., Tammoja, H. Reduction of CO_2 Emissions in Estonia During 2000-2030. Oil Shale, Vol. 24 No. 2 Special, pp. 209-224. 2007 Estonian Academy Publishers ISSN 0208-189X.

In Appendix A, copies of these papers have been included.

Author's own contribution

The contribution by the author to the papers included is as follows:

I Hannes Agabus is the main author of the paper. He is responsible for literature overview, data collection, and calculations. He had major role in writing.

II Hannes Agabus is the main author of the paper. He is responsible for literature overview, modelling, calculations and analysis. He had major role in writing.

III Hannes Agabus participated in writing the paper. He carried out the main description of the power system, provided source data for system calculations and participated in data analysis and calculations. He had medium role in writing.

IV Hannes Agabus participated in writing the paper. He is responsible for literature overview, calculations and analysis. He had minor role in writing.

V Hannes Agabus participated in writing the paper. He is responsible for literature overview, data collection, and calculations. He had major role in writing.

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INTRODUCTION

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are being made to generate electricity from renewable sources.

In recent years, renewable energy sources (RES) have played an increasingly important role in potential energy production. The integration of renewables into energy systems has therefore become a major challenge for system operators, utilities and renewable projects developers etc.

Lately, there has been turning point in the European Union's climate and energy policy. Two key targets were set by the European Council, where reduction of at least 20% in greenhouse gases and a 20% share of renewable energies in EU energy consumption are foreseen by the year 2020. To tackle such climate targets, numerous renewable projects must be erected all over the Europe. Therefore, increasing the share of renewable energy in electricity generation is an important issue everywhere in the world and is not focused solely on Europe.

So far wind has been the main renewable energy source with the highest potential and is the main source to face up to the challenge of secure, sustainable and competitive energy and may displace a significant amount of energy produced by large conventional power plant. Wind energy is assuming importance throughout the world. This rapid development of wind power technology and of the market has serious implications for power systems. The utilization of this renewable source of power is spreading fast to other areas of the world.

Several countries have reached already a high level of installed capacity of the wind power, such as USA, Germany, Spain, Denmark [1], while others follow with high rates of development.

At the end of 2008, there were 121 GW installed worldwide [2]. At the end of 2008, the wind power in the European Union was 65 GW installed capacity, producing 142 TWh hours of electricity, and meeting 4.2% of EU electricity demand [3].

The optimistic projection for 2020 is 1500 GW installed worldwide and 230 GW in EU, of which 40 GW should be offshore wind. In 2008, over 40% of the EU’s new capacity was wind energy and a record-breaking 27 GW of new wind power generation capacity came online on a global level.

Targets in Estonia for new renewable electricity supply were set at 5,1% (ca 400 GW/h) from gross inland consumption by 2010 and 25% by 2020. The current share of wind power in Estonia is 108 MW (June 2009). As onshore wind development in Estonia is quite limited, the offshore wind park projects will have a huge role to play in the near future to fulfill the set targets. Also new Estonian Electricity Sector Development Plan up to 2018 [4], where 30% share of wind generation in total installed capacity is foreseen by 2018, appoints the substantial share of onshore and offshore wind power in the near future. However, planned developments can propose severe challenges to the integration of wind power into the existing power system. It is also transparent that RES-based power generation sources are not competitive without additional subsidies.

The idea of wind power is to reduce the domination of fossil fuel together with lower emissions. This issue is very important in Estonia and other countries (Poland, etc.), where mainly fossil fuel based thermal power plants are used for power generation.

The purpose of the thesis is to present the main technical-economical challenges associated with the integration of wind power into the power systems. These challenges include effects of wind power on the power system, the power system operating cost, power quality, power imbalances, power system dynamics, and impacts on transmission planning.

The work concentrates on the impact of large-scale wind power on the power system operation and Estonian power system is used as the reference case. The main focus is both on short term effects (wind power forecasting, operating reserves, generation scheduling) and long term effects (installed wind power capacity, transmission capacity).

ACKNOWLEDGEMENTS

The thesis has been strongly influenced by the late Professor Olev Liik who guided me through my studies at TUT; supervised my MSc during 2002-2004 and this work from 2004 up to August 2005.

I would like to express my special gratitude to Professor Heiki Tammoja who took over the task of supervision, offering encouragement and valuable advice in finalising the work.

Special thanks go to my good colleagues Ivo Palu and Mart Landsberg for supporting me during preparation of this thesis.

I would like to show my graditude to Nordic Energy Research for supporting me on my research.

Also I would like to express my gratitude to colleagues Rein Oidram, Oleg Tsernobrovkin, Jako Kilter and Mati Keel - the co-authors of several articles and pieces of scientific research.

During the research I have received constant support from many individuals - Thank you all!

My ultimate gratitude goes to my parents, my sister and My Girl for extraordinary patience and understanding during the critical times.

1 CHARACTERISTICS OF WIND POWER

It is a well-known fact that the wind turbines are almost uncontrollable and wind power varies rapidly and frequently within a wide range, as their output power is a function of the wind speed in the third degree, their generation is hard to forecast and they cause additional investments into the system.

Characteristics of wind power are different and therefore its integration leads to some important challenges concerning the power system. Due to weather dependence, the availability of electricity generated from wind energy differs fundamentally from that generated conventionally from fossil fuels.

1.1 Capacity factor

When capacity factor for conventional power plants is typically 40% to 80%, then despite the high availability of the wind turbines (98%), the capacity factor rarely reaches beyond 30% for onshore wind power and 40% for offshore wind power. Therefore, one installed megawatt of wind power cannot replace one megawatt of thermal power [5, 6].

Wind power generation is highly dependent on the wind resources at the site. For most sites and land the average power as the percentage of the nominal capacity (capacity factor) is between 20% and 40% (full load hours of 1800-3500 h/year) [7].

Prognosis of capacity factors of wind parks in different locations in Estonia are presented in [III]. Average capacity factor for current operational Estonian onshore wind parks is around 30%.

1.2 Variability and uncertainty an related to wind generated electricity

Many system operators are concerned that wind power may cause power flow imbalances on their systems. They are concerned about the perceived unpredictability of wind. Wind could blow when the load requirements are low. This could cause too much power to flow on a electricity system. They would have to then shut down the wind power and thus lose its benefits. On the other hand, when they need the output from wind generators, the wind may not be blowing [8]. Wind speed and power output of wind turbine are random processes [9, 10]. For large-scale wind power, it is the wind variability that leads to the largest generation variations [7]. As it could be seen in Fig. 1-1, the gap between predicted and measured wind could be quite substantial.

The inherent variability of wind generation will require more resources to be made available in order to manage short-term balancing between demand and supply. However, the amount of additional resource required for managing the unscheduled wind power will not be on a megawatt for megawatt basis. The key factor here is the phenomenon of geographic diversity of individual outputs of wind parks.

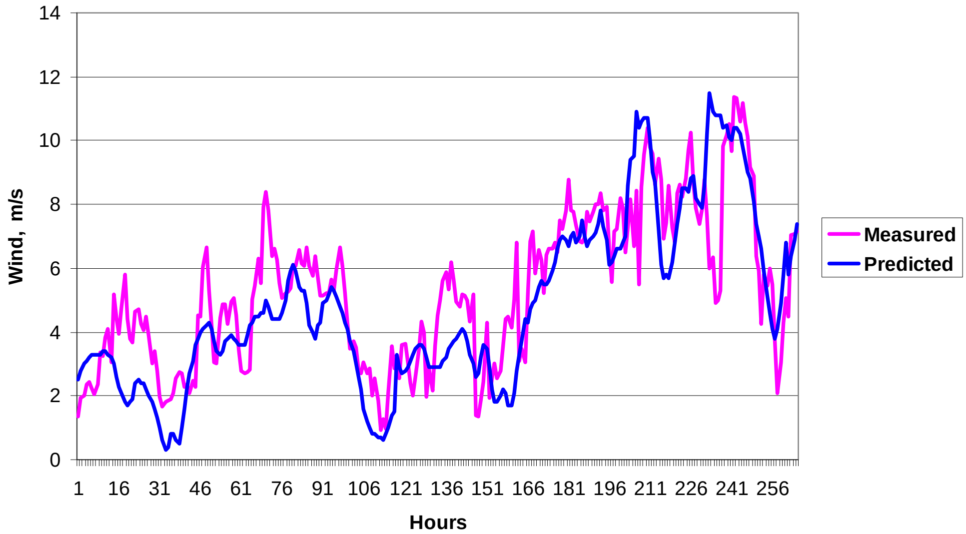

Figure 1-1 Example section of measured and predicted wind speed comparison on wind park site in Autum 2008 [11]

Wind power generation introduces more uncertainty in operating a power system as it is continuously variable and difficult to predict [6, 10].

The output of individual wind turbines is generally not highly correlated, particularly when wind farms are located in different regions. Hence, system operators need to deal with the variability of the net aggregated output of a large group of wind parks, rather than with the variations in the output of individual wind park.

The magnitude of wind output fluctuations will also strongly depend upon the time horizon considered. Clearly, the magnitude of wind fluctuations increases as the time horizon under consideration becomes longer.

Statistical analysis of the fluctuations of wind output (for an assumed annual wind generation profile) over the various time horizons can be performed to characterize the variability in wind output. If the fluctuations of wind were perfectly predictable, the additional cost of operating the system with a large penetration of wind power would not be very significant provided that there is sufficient flexibility in the conventional plant to manage the changes in wind [12-15].

In general, wind power prediction has to provide two types of information: the forecast itself and a measure of uncertainty of the forecast. Knowing the uncertainty enables users to assess the risk of trusting the prediction which, e.g., helps energy brokers to decide on making a bid on the spot market.

A way of reducing the uncertainty associated to wind power production is to use forecasting tools and models.

More different variability and uncertainty factors related to wind power forecasting are reviewed in [16].

1.3 Forecasting wind power generation

In an power system with an important share of wind power, new methods for balancing supply and demand are needed. Wind power generation forecasting plays a key role in tackling this challenge. Good wind power predictions increase the value of wind power making it more competitive. Fig. 1-2 shows the hourly power fluctuations and forecast of wind power at the wind park in October 2008.

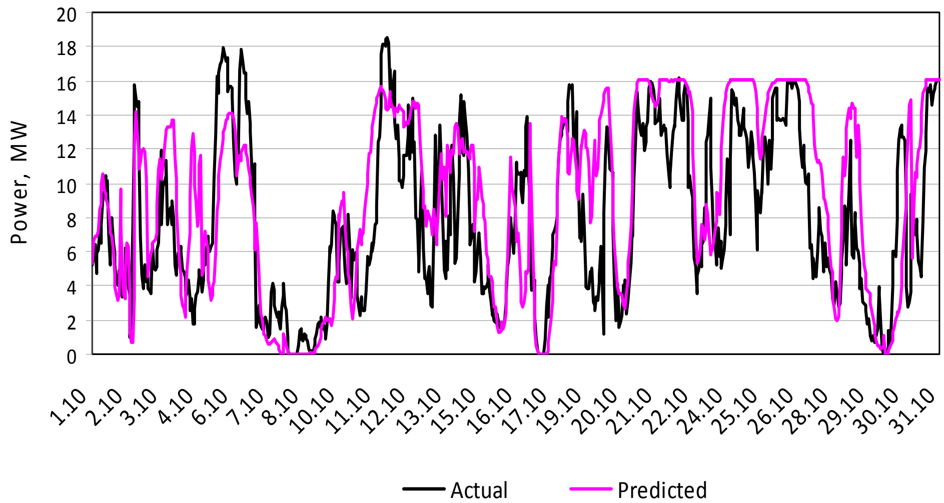

Figure 1-2 Predicted and actual generation of wind park in Estonian power system during October 2008 [4Energia]

For short-term ("day-ahead") wind forecasts, up to several hours ahead, persistence-based techniques are generally used, while for longer horizons, forecasts based on meteorological information are frequently applied.

Wind forecasting has substantial value and its payoff is primarily in the day-ahead time frame through its influence on unit commitment decisions [8, 10].

Due to the wide range of spatial and temporal scales that determine the variations in the generation of wind power, it is necessary to use a diverse mix of data sources and types to achieve the best possible forecast performance. For wind power forecasting, the most fundamental type of data is the time series of meteorological forecast for entities (like wind speed, etc.) and power generation from the wind park itself.

There are multiple forecasting tools available. Wind power prediction models used in the wind power forecasting process could be either a physical model or statistical model. There are many types of models within each of these major categories [12, 17, 18].

There is considerable activity in the area of wind prediction and although significant developments have been lately made with wind power forecasting tools (such as neural networks), further improvements in the accuracy of wind prediction are expected [19].

Forecast errors depend mainly on the forecasting tool used (Fig. 1-3) [11], the amount of information available to make the forecast and the fixed delivery (spot market) gate-closure time, which defines how much ahead the forecast has to be made.

Two standards are commonly used to represent the forecast error, namely the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) or Mean Absolute Percentage Error (MAPE) [8, 13, 17].

Commonly, it is acceptable if MAPE is 20% at the maximum [16], while some errors in high wind might be as large as 35% or more [20, 21].

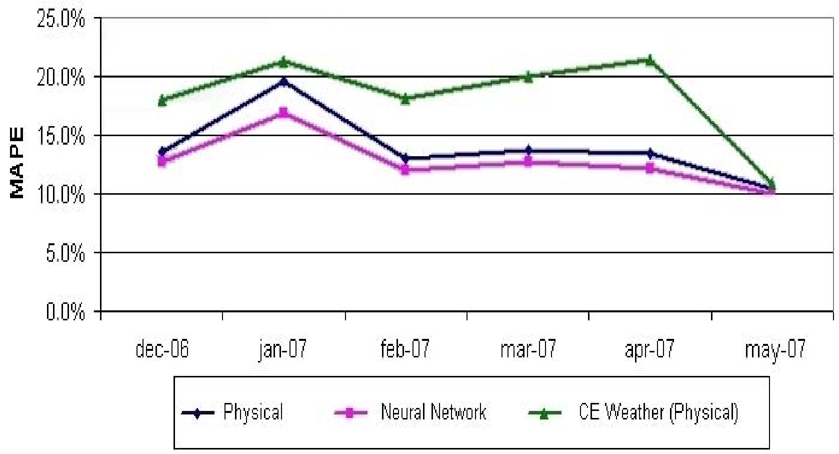

Figure 1-3 Forecast performance with different forecast models [11]

The quality of wind power forecast significantly improves as the forecast horizon decreases [22]. With usage of adequate forecast system, the reserves held for wind power will be decreased and the resulting surplus power could be offered by the conventional units e.g., the intraday market.

More solid reviews and analysis related to wind power forecasting could be found in [20, 23, 24].

2 IMPACT OF WIND POWER GENERATION ON THE OPERATION AND DEVELOPMENT OF THE POWER SYSTEMS

2.1 Wind turbines cooperation with power system.

Wind power is by many considered to be a key technology along the pathway towards a sustainable power generation system. With wind becoming an important alternative for the generation of electricity, it is essential to accurately model the effects of wind power on the entire power system, especially regarding the underlying economics [17].

Integration of wind generation in the operation and development of the power system is associated with both benefits and costs [12]. The main visible benefit of wind power is to reduce the domination of fossil fuel together with lower emissions. It is technically possible to integrate considerably large amounts of wind power into the power systems, the limits arising from how much can be integrated at socially and economically acceptable costs [6].

Since the wind power has impacts on power system operational security, reliability and efficiency, the main drawbacks of wind power from the power system point of view is its variability and unpredictability. Therefore, various forms of additional reserves will be needed to maintain the balance between supply and demand at all times [12, 25]. Clearly, the capacity value of wind power generation will be limited as it will not be possible to displace conventional generation capacity on a "megawatt for megawatt" basis. In order to maintain the risk of system security at appropriately low levels, the installed capacity of generation must be greater than the peak demand. This is necessary for dealing with failures of generators and uncertainty in demand [12].

There are a number of issues associated with the integration of wind power in system operation and development. Although penetration of wind power generation may displace significant amount of energy produced by a large conventional plant, concerns over system operation costs are focused on whether wind generation will be able to replace the capacity and flexibility of the conventional generating plant. Furthermore, the location of these new sources will be of considerable importance in assessing the impacts on the transmission and distribution network infrastructure.

Large penetration of wind power generation will have strong cost influence on the power system containing large conventional power plants. Here, the power plants must deliver both the flexibility and reserve necessary to maintain the continuous balance between load and generation and additional fluctuating wind power would increase the fuel consumption and total system emissions level.

For power generation systems which contain a significant fraction of wind power, the wind parks are typically distributed over a certain region which limits the influence of variations in wind speed for statistical reasons [5]. However, one unit of wind power capacity added to a system with a certain fraction of wind power will replace less conventional capacity than the first wind power unit added to the system, assuming the same pattern in the wind power characteristics (wind conditions and distribution of wind parks).

Aggregation of wind power over larger geographical area, apart form smoothing out variability, improves the quality of the forecast because of the partly uncorrelated characters of the forecasts errors. As a result, both the reserves held and the actually applied in a control area are decreased. Balancing wind power across control areas is even more efficient [22, 26].

It must be noted that wind turbines are generally not able to provide the range of system support services (e.g. voltage and frequency regulation) that are provided by conventional thermal and hydro power plants. This can usually be tolerated at relatively low levels of penetration, but at the higher levels indicated by the target it will require systematic solutions in order to maintain stability and integrity of the transmission system [12].

Large-scale integration of wind power into the power system needs to address the challenge of designing integrated regulation strategies of overall power systems [25]. In order to make possible a large-scale integration of wind power, while safeguarding a high security of supply, economically acceptable ways to handle variations in wind power generation need to be identified [5].

The feasibility of wind power development depends on the ability to produce energy at very low operating costs [17]. To enable a proper management for large-scale wind power, more flexibility will be needed in the power system. Flexibility could be achieved in generation, demand or with adequacy of transmission capacities between interconnected areas [6].

High penetration of wind power has impacts that have to be managed through proper power plant interconnection, integration, transmission planning, and system and market operations.

The integration of large amount of wind turbines into the power system depends on the ability of other units in the system to meet the wind power variations. In Estonia there are quite limited options for balancing wind power fluctuations as there are no fast-starting generating units available in the power system and existing thermal power plants balancing capabilities are quite limited.

Nevertheless, large-scale wind power still lies in the future for many countries. At high penetration levels, an optimal system may require changes in the conventional capacity mix [27].

From the side of wind energy enthusiast, wind power integration benefits are expected to be significantly higher than the integration costs as wind power replaces fossil fuels and therefore reduces the system total operating costs and emissions.

Wind power integration and its influence to the power system operation is a complex problem. A lot of research has been conducted to understand wind park operation and its behavior in different contingencies [28, 29, 30]. Besides the direct connection of wind parks to the power grid and related problems also different reserves and their requirements in case of wind power must be considered [31].

2.2 Problems of balancing the fluctuations in wind power

2.2.1 Balancing resources

The power system requires a constant accurate balance between generation and consumption. It is therefore necessary to have reserve capacity available that can provide the required regulating power at short notice [12, 32].

The growing share of wind power is accompanied by an increasing need for reserve capacity, which is necessary to ensure that it is always possible to balance the entire system [32].

Both the operational and disturbance reserves are divided into different categories according to the time scale within which they are operating. Power system reserves are commonly split into three levels [10, 32, 33] and they are characterised by differences in the time needed to activate the reserve:

- primary reserve;
- secondary reserve;
- tertiary reserve.

The objective of primary control is to maintain balance between power generation and demand using turbine speed governors [33]. Primary control is performed on a time scale of seconds/minutes. On this time scale, there is no correlation between the variations of geographically dispersed wind parks.
Secondary control makes use of a centralized automatic generation control, modifying the active power set points of generators in the time-frame of seconds to typically 15 minutes [33]. Its deployment duration is limited by technical and economic reasons to about 30 min. For continuing imbalances tertiary reserve must be manually activated [8].

Tertiary control uses tertiary reserve (15 minute reserve) that is usually activated manually to free up the secondary reserves and to optimize the power plants.

Secondary and tertiary reserves are necessary to cover fluctuations on the power generation side (e.g. wind) and require the activation of additional capacity.

Gas turbines or even more quickly reacting pumped storage power plants, which can activate their full capacity within a few minutes, are counted as standing tertiary reserve, while the spinning tertiary reserve is constituted by the unused capacity margin of power plants already operating. Providing spinning reserve thus means plant operation at partial load with a reduced efficiency [6].

Traditional balancing resources include [10, 22, 34]:

- hydro and pumped storage power plant;
- gas turbine (OCGT, CCGT);
- traditional thermal power plant (TPP) and some nuclear power plants (NPP);
- wind under curtailment (i.e. operating below its maximum available output);

- demand dide management (DSM);
- In future, more and more new technology energy storage devices will contribute, but they are currently expensive and of modest size.

Power systems that contain considerable amount of hydropower are in a favoured situation because hydropower is controllable, fast and also renewable.

Gas turbines suit best for covering peak load and acting as disturbance reserves. High price of natural gas and low efficiency on small load makes it not practical to use gas turbine power plants for constant control of the load curve.

To analyse the ability of power systems to control area power balance, the interchange power changes hold the key position. Precisely the values of maximum deviations in interchange power values guarantee the safe operation of power systems and quality of electricity.

2.2.2 Balancing market

The balancing market is a physical market, as all traders correspond to actual power flows. Any power that is sold in the day-ahead market but not delivered in real time is deemed to be purchased in the balancing market from the system operator at the imbalance energy price (single imbalance pricing, dual imbalance pricing).

The balancing procedure can be described from two perspectives:

- the use of balancing services for the imbalance settlement;
- the provision of balancing services on balancing service markets.

Balancing responsible parties are generally all generating units or traders. All of them are required to submit day-ahead schedules to the system operator that estimate their electricity feed-in or consumption. Schedules can be modified before the fixed delivery (spot market) gate closure which is generally 1-3h before real-time delivery [35].

A great variety of balancing service market designs exist with respect to pre-qualification requirements, bid evaluation and settlements rules of balancing service markets [36].

2.2.3 Balancing system and wind

For operational reserves, the unforeseen variations induced from wind power are relevant on the time scale of 10 min...1 hour. To estimate the impact of wind power on the secondary reserve, wind power variations are studied in combination with load variations: the net load is the load minus the wind power production for each hour [33].

The increase in reserve requirement for wind power is mostly estimated by statistical methods combining the variability of wind power to that of loads [6].

Wind power has no influence on the disturbance reserve as long as wind parks are less than the largest generating unit in the system.

The power plants have different possibilities of control. Since the cost of reserves depends on the type of the power plant, then some of these control mechanisms (hydro, pumped storage, gas turbine, etc.) are the most efficient to cover system balance errors caused by wind power fluctuation. Hydro power is usually the cheapest option and gas turbines are more expensive ones.

Until all the fluctuations of wind power can be compensated with hydro power plants, the integration of wind parks does not trouble the existing systems too much. The situation is different in power systems (Danish, Polish, Estonian, etc.) that include mainly TPP's, as their speed of increasing and decreasing of power is limited.

For that reason the compensation of wind power generation with thermal generating units might not decrease but even increase the fuel cost and emissions in the power system [10, 33, 37].

A simple means of balancing the system and reducing the grid load can be provided by the downward regulation of wind power generation in periods of substantial wind power generation. A reduction in wind power generation also makes it possible to use wind turbines for providing both upward and downward regulation [22, 26, 32].

Large balancing areas and aggregation benefits of large areas help to reduce the variability and forecast errors of wind power as well as help in pooling more cost effective balancing resources. When a power system is interconnected with other power systems, there is possibility to lead wind parks' generation to other power systems. At that case the regulating power plants in these power systems must regulate all the wind power changes, absorb most of the wind power generation and also suffer the losses of wind power compensation [6, 39].

For example, in the synchronously operated Nordic area the primary reserve has been 600 MW for 360 TWh/year demand. Assuming an increase relative to how much variable consumption there is, producing 10% of the demand with wind power (36 TWh/year; 18 GW wind power) would increase the primary reserve by 10% [7]. This means an increase of 60 MW or about 0.3% of the wind power capacity installed.

To estimate the impact of wind turbines on power system operating reserves, it has to be studied on the basis of a control area. Every change in wind output does not need to be matched one-for-one by a change in another generating unit moving in the opposite direction. It is the total system aggregation, from all generating units and consumption with its uncertainty, which has to be balanced [6].

System operators are concerned that variations in wind park output will force the conventional power plants to provide compensating variations to maintain system balance, thus causing the conventional power plants to deviate from operating points that are chosen to minimize the total cost of operating the entire system. The concerns of operators are compounded by the fact that conventional power plants are generally under their control and thus are dispatchable, whereas wind turbines are controlled instead by nature [8].

For a producer selling wind power generation on the electricity market there is a clear benefit in trading as close to the delivery hour as possible, since this reduces the prediction error and thus the extra cost from regulating [7].

Regulation power almost always costs more than the bulk power available on the market. The reason is that it is used during short intervals only and it has to be kept on stand-by. The cost of increased reserve in the hydro power system is also difficult to obtain. Thus, the cost is estimated in two ways: based on thermal capacity costs and on existing regulating power market prices [6, 7].

The lowest overall power costs to the consumer are usually obtained when the peak-load increment is very small and a steady base-load utilises all of the available generating capacity fairly constantly. Therefore, additional fluctuating wind power capacity creates an additional need for peak power and creates problems with system-balancing.

It is important to understand that the key issue is not whether a system with a significant amount of wind capacity can be operated reliably, but rather to what extent the system operating costs are increased by the variability of the wind [8].

2.3 Wind power and transmission grid planning

Proper interconnected transmission grid with sufficient transmission capacity is the key to aggregation benefits, electricity markets and larger balancing areas.

The impact of wind power on transmission depends on the location of wind parks relative to the load, and the correlation between wind power generation and electricity consumption areas [38, 6].

Wind power affects the power flow in the network. It may change the power flow direction, reduce or increase power losses and bottleneck situations, especially in grids with high wind power concentration areas where local electricity consumption is low.

The general transmission grid planning consists of three aspects which have to be considered when planning the integration of large amount of wind power into the power system [13]:

- adequate level of operational security;
- adequate transmission capacity;
- functioning of electricity market.

When integrating large amounts of wind power into the transmission system, more transmission capacity must be built or existing power flows of some corridors in normal operation must be restrict.

There are a various means for maximising the use of existing transmission lines like use of online information (temperature, loads), FACTS (Fast Access Control Technology Solutions) and wind power output control-forecast.

Extra grid reinforcement may be necessary to maintain transmission adequacy and security. When determining adequacy of the grid, both steady-state load flow and dynamic system stability analysis are needed. Different wind turbine types have different control characteristics and consequently also different possibilities to support the system in normal and system fault situations. For system stability reasons the operation and control properties will be required from wind turbines at some stage depending on wind power penetration and power system robustness areas [6, 8].

The grid reinforcement costs are not usually continuous as there can be momentarily single very high cost reinforcements needed (i.e large-scale offshore wind park integration).

The cost of grid reinforcements due to wind power is depending largely on the location of wind turbines in relation to load and grid infrastructure, and this varies from country to country [6, 39]. For example, according to recent studies in Denmark, additional 3 GW of wind integrations will cost around 53-994 EUR/kW, depending on whether cabling or overhead lines (OHL) will be used [6].

For high penetrations of wind power there will be a need for increased generation flexibility, transmission to neighbouring areas, demand side management or even suitable storage (pumping hydro, thermal storage, batteries, hydrogen and fuel cells).

Grid connection is very important financial issue for all the renewable projects, especially if the integration of RES plants requires heavy grid reinforcement.

In most European countries, RES have priority access to the grid. However, even inside EU, grid connection charges are treated quite differently [35], [39]. In Germany, only the costs of the physical connection to the nearest grid connection point have to be carried out by the RES project developer. Wider grid reinforcement investment costs are split among all the network users (transmission service tariff). In Spain and now also in the UK, only certain share of grid reinforcement costs has to be carried by wind park developer. While in Estonia, all connection and grid development costs have to be compensated by the wind project developer. This gives an incentive to minimize grid reinforcement costs, but burdens high costs on the project developer and usually decides the project’s future.

2.4 Technical requirements

Wind parks must provide control and regulation capabilities existing in conventional power plants, necessary for safe, reliable and economic operation of the system.

There are different technical requirements applied for wind turbines in various power systems. Even among EU countries there are different Grid Code requirements applied [40-42]. Good surveys of local standards and technical requirements in different countries are presented in [27, 50].Nevertheless, main common requirements of Grid Codes are:

- fault ride through (FRT) capability;
- voltage and frequency operating limits (possibly for limited time and at reduced output);
- active power control (set-point, ramp rates, reserve, frequency regulation);

- reactive power control (Q/PF control, voltage regulation);
- other requirements (power quality, short-circuit current, measurements, protection, communication, etc.).

Present technology of wind turbines and wind parks can be designed to meet industry expectations such as FRT, supplying reactive power to the system, controlling terminal voltage, and participating SCADA (Supervisory Control And Data Acquisition) system operation with output and ramp rate control [14].

Grid reinforcements may be needed for handling larger power flows and maintaining a stable voltage, and is commonly needed if new generation is installed in weak grid far from load centres [6].

If there is much wind integrated into the power system and conventional power plants units are economically forced to standby mode, then it may not always be the case in the future, so it must be possible to make a black start of the system without these units [32].

Because of large differences and deviations existing between national (even regional) codes, there is need for a more uniform approaches and introduction of Grid Code compliance tests for wind turbines (standardization).

Many transmission problems and stated grid connection and operation rules are covered more deeply in [14, 43]. Many wind power related technical issues and different Grid Code requirements are examined in [10, 43, 44, 45].

2.5 Power quality and weak grid

The most important factors in installing wind turbines and connecting the turbines to the existing grid are sufficient transmission capacity of the grid and the issues of power quality. If the grid is not substantially expanded, both problems can be considered technical restrictions that have to be fulfilled and used for calculating the permitted capacities of wind turbines connected to the grid depending on the planned connection point [XI, XII].

Wind turbines are installed in locations with sufficient wind energy. In many cases these locations are not in densely populated nor in industrial areas, which could guarantee an existence of stronger power grid.

Wind turbines in common strong power systems might have a direct impact only on voltage: voltage change, flicker, harmonics and transients. These are values, which also characterise the so-called weak grid.

Poor power quality can cause the end user's equipment to operate inefficiently, i.e., lights to flicker, or the utility system becomes unstable and disrupts power to the customer.

Load fluctuations cause in the steady-state operation voltage fluctuations, especially in weak grids with long transmission lines and relatively low voltage. Connecting wind turbines to this grid increases those fluctuations because of short and long-term changes in output power. The input of active and reactive power might change the voltage in the connection point or in any point close to it. One parameter that also describes weak grid is a low short-circuit power.

Power quality problems caused by wind power are best solved at the point of interconnection of the wind turbine to the power grid [8].

Due to unique character of every grid and various types of wind turbines it is difficult to evaluate the impact of different factors without measurements and/or exact modelling.

3 ESTONIAN ENERGY SYSTEM AND MARKET

3.1 Basic energy data

Estonian main fuel for power plants is oil-shale and 94% [46] of electricity generation base on its combustion. Electricity generation is concentrated into two oil-shale fired thermal power plants in Narva region [II]. In the end of 2008 oil-shale fired power plants in Narva region had an installed capacity of 2000 MW, gas fired Iru CHP 176 MW and small thermal power plants 116 MW. There was only 5 MW of power installed in small hydro power plants and those are run-through type with no water reservoirs. Estonian total installed power was 2362 MW and domestic peak power demand approximately 1500 MW. Domestic low load in summer decreases to 450 MW [46]. Total final consumption in Estonia in 2008 was approx. 7 TWh. In 2009, there was two new peat and biomass based CHP's (2x25 MW) connected to the power system, one in Iru (Väo CHP) and the second in Tartu (Anne CHP). There is also new CHP development project in Pärnu (another 25 MW), what is planned to come into commission in year 2010.

Oil-shale fired thermal power plants will stay as two major energy producers in Estonia at least until 2015. Afterwards, accordance under determined CO_2 and SO_2 refuse limits, set on environment strategy, large amounts of old powder–burn technology energy units must be closed and displaced or intense improvements must be made to meet new requirements. This will give change for escalation of new CHP's, wind power, gas turbines and ambitious nuclear power development plans [II, 47].

3.2 Wind power in Estonia

Estonia has a national target to increase the share of renewable energy in the electricity generation up to 5.1 % (ca 400 GW/h) from gross inland consumption in 2010 [III, IV]. Presently, the purchasing obligation and subsidies for electricity from RES have been written into legislation.

As the interest for wind generation development is growing and it is supported by solid feed-in tariff, the development of new wind power projects has increased. It is obvious that new declared EU renewable energy sources directive, which rises the Estonian target up to 25% from gross inland consumption in 2020, will have impact on wind generation volume.

Recently, the Government of Estonia approved new Electricity Sector Development Plan up to 2018 [4], where 30% share of wind generation in total installed capacity, is foreseen by 2018. According to the development plan, 400 MW of onshore wind power and 500 MW of offshore wind power are foreseen by the end of 2018. Also 900 MW of fast-starting generating units should be built for covering wind power fluctuations.

Wind conditions in Estonian coastal areas are comparable with those on the coast of Spain and the inland of France and Germany (average wind speed 5.5-6.5

m/s). The most attractive wind areas in Estonia are comparable with those of inland of Denmark.

The highest potential in wind energy use in Estonia has Saaremaa island [III] which has excellent wind conditions (Fig. 3-1) but it cannot be considered as the solution for covering the local electricity balance due to various limitations such as low local consumption and weak local grid. Also, nature protection areas of Natura 2000, the centrepieces of EU nature & biodiversity policy, will cause additional constraints for wind power development.

Nevertheless, the development of wind power use has led to a noticeable contribution to the energy supply in Estonia. The current share of wind power in Estonian energy system is 108 MW (June 2009). Around 200 MW is currently under construction. The largest wind farms are Paldiski 18.4 MW, Viru-Nigula 24 MW, and Rõuste 8 MW. The biggest 39 MW wind park was opened in June 2009 in Aulepa.

According to Estonian TSO (Elering OÜ), the overall amount of wind power capacity that is applied for connection is already over 4000 MW, including two large-scale offshore wind park development project (Fig. 3-1). It is a huge number compared to overall consumption. Consumption forecast, made by Estonian TSO, is foreseeing winter peak load for year 2010 according to most probable base scenario 1665 MW and for year 2020 it will be 2016 MW. So it is clearly seen that the capacity of planned wind farms is decidedly exceeding the foreseen peak demand until year 2020.

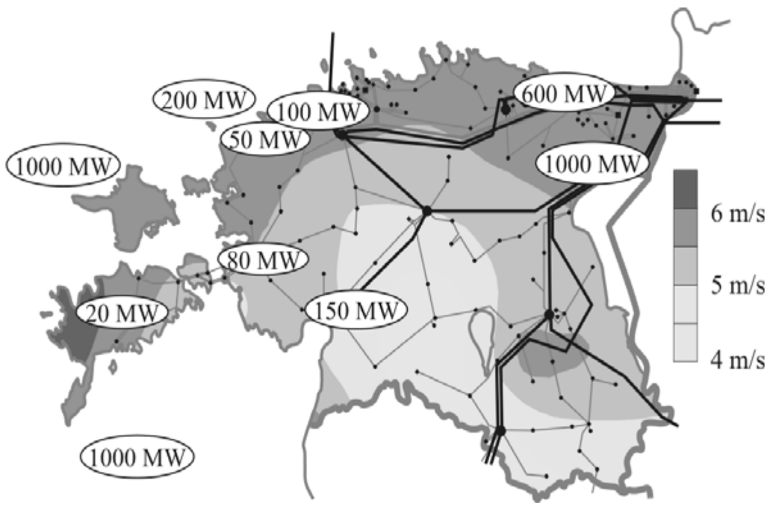

Figure 3-1 Estonian wind resources, transmission network (110…330 kV) and possible locations of the wind parks and their output (MW) according to connection applications, perspective of 2020 and later

Such large-scale integration and prediction of wind power is challenging in terms of power system management. It requires corresponding heavy investments into electrical networks and power plants to provide transmission capacity, control services and required generation reserves [II, III].

3.2.1 Support schemes for wind electricity

The current feed-in price for produced and sold electricity is 7,4 EUR cents per kilowatt-hour up to generation capacity 200 GWh/year, afterwards the price will be 5,4 EUR cents per kilowatt-hour until the wind energy annual limit for support 400 GWh/year is reached [48]. The subsidy system development in Estonia is presented in Fig. 3-2.

The producer has the right to get a support price for 12 years from the start of generation. Estonian TSO reviews its support for renewable electricity annually and publishes its policy for the next calendar year on its homepage on 1 December at the latest [49].

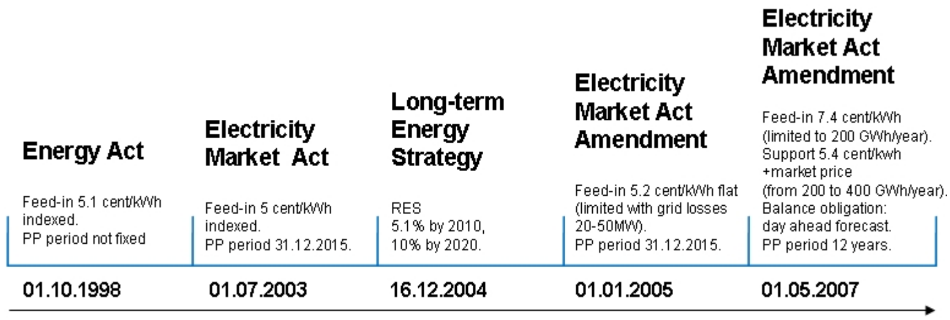

Figure 3-2 Wind power support system development in Estonia

Renewable energy support in Estonia is still low compared to the support level in other EU countries (Denmark – circa 120 EUR/MWh, Germany – 150 EUR/MWh). There must be more supportive arrangements enforced before the Estonia will achieve the set targets.

There are already some major changes expected in legislation. According to proposed amendment to the current Electricity Market Act, the support level for wind power will be increased up to 600 GWh/year. Amendment is expected to be legalized by the Parliament in the beginning of fall 2009.

3.3 Electricity market

The opening of the electricity market has been slower in Baltic countries compared to the rest of EU, where all electricity consumers are already able to choose their electricity provider as of July 2007. Since 1999 the Estonian electricity market has been open for eligible customers whose annual consumption exceeds 40 GWh. These consumers have the right to purchase electricity from any producer or seller in the market with an obligation to pay for network services. In 2008 there were 13 eligible consumers.

Non-eligible customers can purchase electricity from the grid company which they are physically connected to or from the seller named by the respective grid company.

The consumption by eligible customers presently forms ca 10% of the total electricity consumption. During the accession negotiations, Estonia and the EU reached a compromise solution for further step-by-step opening of the electricity market. Starting from January of 2009, 35% of the Estonian market was opened. Full opening of the electricity market is planned to be completed by the year 2013.

The market will operate according to the rules of the Electricity Market Act and the Grid Code.

The current electricity trading in the market is carried out by bilateral contracts. All market participants have to have an open delivery contract and balance providers need a balance agreement with system operator (Elering OÜ).

There are four balance providers in Estonia who are daily participating in the electricity market actions.

Long negotiations have been going on for Nord Pool (Nordic power exchange) expansion towards Baltic countries. Nord Pool Spot “Estlink” price area is planned to be finally established in April 2010. Before that will happen, numerous decisions have to be made, current laws need to be changed and considerable arrangements achieved inside the Baltics.

3.4 Power grid

Estonian power system is operating in parallel with the power system of IPS/UPS of Russia. Estonia, together with other Baltic power systems, Latvia and Lithuania, are the only EU countries that belong to synchronous zone of IPS/UPS of Russia. Therefore, its operational requirements are somewhat different to the rest of Europe.

Estonian transmission grid is based on 110-330 kV lines and currently the grid condition is sufficient. Estonian transmission capacity is heavily influenced by the power transit (primarily Russia-Latvia). Also, power transit through the Estonian system is uncontrollable by Estonian TSO as it is submitted by the Russia and electricity trading [II].

Estonia has a very good interconnection with Russia and sufficient interconnection with Latvia. Estonian power system is interconnected to neighbouring countries with five 330 kV transmission lines. With Latvia, Estonia has two 330 kV lines – one from Tartu and another from Tsirguliina substation. With Russia, Estonia has three 330 kV interconnection lines – one from Balti PP, second from Eesti PP and third from Tartu substation. Interconnections to the neighbouring areas have the capacity of about 2000 MW. In addition to these, since year 2006 Estonia has a 350 MW HVDC connection to Finland (Estlink) which has made it possible for power market participants to enter into the Nordic power market. Nevertheless, substantial reinforcements of interconnections and development of inland grid are needed for maintaining the power system security of supply and cope with the high level of wind power penetration.

It has been already decided that there will be second interconnection with Finland (Estlink 2) and it should be operational in year 2014 (Table 3-1). This additional interconnection should increase the reliability of the power system in the Baltic States, while decreasing the dependency from Russia. Furthermore, the enhancement of the interconnection capacity will be helpful for integrating the future power market of BALTSO (Organization of Baltic Transmission System Operators) area with Nord Pool. At the moment the right-of-way selection for the underground cables of the Estlink 2 is already finished. The arrangement for selecting the right-of-way for the new HVDC submarine cables is in progress.

Estonian grid development plan foresees the establishment of that new 330 kV connections between Tartu-Viljandi-Sindi-Harku substations. The new 330 kV transmission lines will reinforce the connections between north and south 330 kV networks and provide better reliability in Tallinn and Pärnu region. Additionally the new transmission lines provide better opportunities for connecting new wind parks to the transmission grid. The connection is planned to be built during 2012-2018.

One possible new HVAC interconnection is Sindi-Riga 330 kV OHL (year 2017-2018) which would form an important part of energy corridor between Northern and Central Europe.

Table 3-1 Planned power system interconnections between neighbouring countries

Interconneciton*	From-To	Technical solution	Capacity (MW)	year
Fenno-Scan 2	Finland-Sweden	DC Submarine cable	800	2010
Estlink 2	Estonia-Finland	DC Submarine cable	650	2014
SwedLit	Lithuania-Sweden*	DC Submarine cable	700-1000	2016*
LitPol	Lithuania-Poland	2x400 kV AC OHL with back-to-back converter	1000	2012-2015

*Possibly additional Latvia-Sweden and/or Estonia-Sweden DC links will be needed to strengthen the market area and secure the security of supply.

Considering the economic growth, demand forecasts, different scenarios of interconnection locations and different types of power plants it is necessary to increase transmission capacity to major consumption regions and install additional power transformers or replace existing power transformers with more powerful ones in major transmission substations [II].

4 ACCOMMODATION OF LARGE-SCALE WIND POWER INTO THE ESTONIAN POWER SYSTEM

4.1 Practice patterns of short-term wind power generation forecast

Wind is a variable resource that is difficult to predict, therefore the variability of wind power presents a special challenge for TSO's and wind park operators. While the output of conventional power plants is nearly constant, the output of a wind turbine fluctuates. To some extent the fluctuations cannot be predicted, they create costs for the power system (e.g. balance power purchase) and consumers as well as potential risks to the reliability of electricity supply [I].

Wind power forecast accuracy is directly connected to the need for balancing energy and hence to the cost of wind power integration. For a time scale from some hours to two days additional conventional reserves have to be kept ready to replace the wind power share in case of decreasing wind speeds. Consequently, a large amount of research has been directed toward the development of good and reliable wind power forecasts in recent years and many different forecasting systems with different approaches have been developed.

In general, a high degree of reliability and accuracy is required by wind park operators and power systems from wind park forecasts. The performance requirements for a forecasting service are dictated by the needs of both the grid owners and the wind turbine operators. The priority is to minimize the deviation between forecasted and actual power plant output [I].

There are a number of physically based methods and statistical techniques incorporating artificial intelligence available for dealing with the problems on all time scales.

On the side of the actual short-term prediction, typical error sources are the wind speed forecast error, power curve modeling and considering the stability of the atmosphere.

Artificial Intelligence (AI) software (such as neural networks), are among the newest signal-processing technologies in the engineer's toolbox which can be applied to reduce systematic model forecast error at a given plant location.

The main drawback of the neural network model and other self-adaptive models is that they need measured values of the power output in the real or near-real time in order to perform the ongoing adjustments. When such measurements are not available, the physically based models can still do a very good job.

The first wind power forecast system in Estonia was introduced in 2007 in Pakri wind park [I, VI].

4.1.1 Description of wind park forecasting models

As a reference forecast, power predictions generated with a very simple physical model were used. This particular physical model converts the predictions of a regional numerical weather model which gives out weather model predictions of wind speed at the 10 m level, adjusted to hub height using a logarithmic wind profile. The obtained wind speed is then converted into power using the nominal power curve.

The forecasted wind park output power could be described as [I]:

$$P(t) = P(v(t), t) + a_1 \cdot D_v(t) + a_2 \cdot \beta; t = 1,...,24 \quad \textbf{(1)}$$

Where; $P(v)$ – wind turbine power curve; v - wind speed, D_v – wind direction, β – site singularity (roughness, etc.), a_1, a_2 – are multipliers.

The forecasted power with Artificial Neural Network (ANN) could be described as:

$$P(t) = a_1 \cdot P_p(D_v(t), v(t), C_w(t), t) + a_2 P_m(t); t = 1,...,24 \quad \textbf{(2)}$$

Where; P_p – predicted power, D_v – wind direction, v – wind speed, C_w – coefficient which takes into account weather forecasts (air pressure, precipitation, temperature), P_m – the measured power from wind park and a_1, a_2 – are multipliers.

The second wind power forecasting model based on ANN uses online power measurements from the wind turbine SCADA system as input combined with highly accurate wind (direction and speed) and weather forecasts (pressure, precipitation and temperature). The program is based on AI (neural network) in order to make the best power predictions through learning.

4.1.2 Evaluation of wind power forecasting

As the test case we used data from an onshore wind park in Paldiski, at the tip of the Pakri peninsula, having a total capacity of 18.4 MW. The study period was one year beginning form June 2007 and during different time periods, one physical based forecast model and one ANN forecast model were introduced. Power output data and information about wind turbine availability were available in 1-hour resolution. Seasonal variations of wind power are clearly present in Estonia. This means that there is usually more generation during winter than in summer.

The general forecasting errors could be caused by: 1) inaccurate wind prognosis; 2) insufficiently calibrated power forecast model; 3) human factor (forecaster); 4) insufficient wind park maintenance planning.

Illustrative predicted and actual generation of wind power in Pakri wind park is shown in Fig. 4-1.

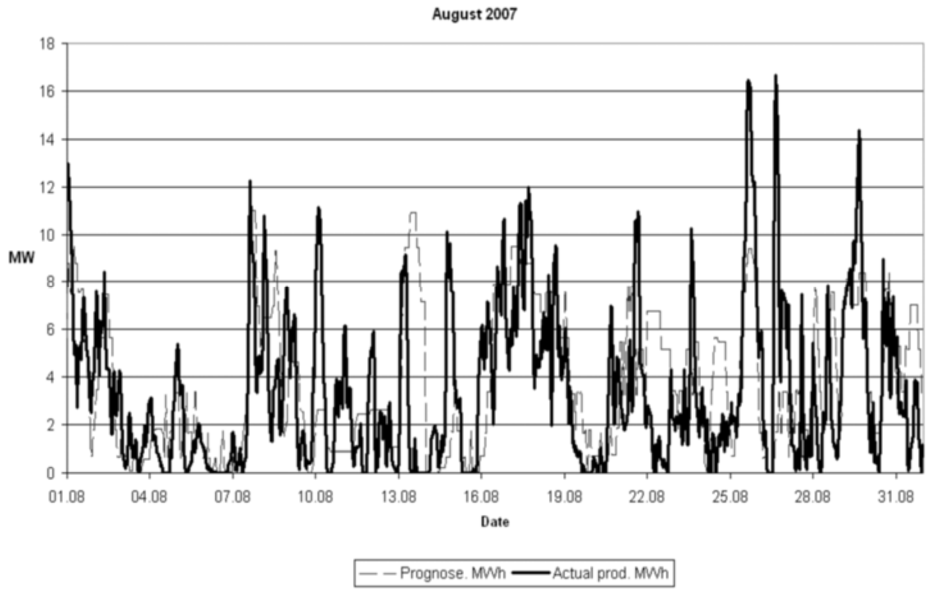

Figure 4-1 Predicted and actual wind power generation in Pakri wind park, August 2007. Time series plot, 0-24 hours [I]

Summary of the one year forecast performance results is presented in the following table. In Table 4-1 monthly values of the mean absolute error as percentages of the total installed power are shown for the first 24 hours in hourly resolution.

Table 4-1 Wind power forecast performance results with simple physical model, June 2007 - February 2008 [I]

Parameter	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Veb
MAPE (%)	16	15	14	19	12	18	21	29	17

It is noticeable that two month MAPE values are above reasonable (more than commonly accepted 20% [16]). Level of accuracy should be improved when combining predictions for larger areas.

For the Nord Pool electricity market, the MAE of wind power prediction is 8-9% of installed capacity, what is very good result. The error in the amount of electricity produced is already 38% of the yearly wind power generation [7].

Wind power forecast performance results with ANN model were: the average MAPE was 16%, the minimum MAPE was 14% and maximum MAPE was 18% (results of spring 2008). The neural network engine is in average 3% better than the ordinary forecast approach.

4.1.3 Performance results

From the two model performance results shown, the following conclusions can be drawn [I]:

- The physical model performs below average;
- The neural network model perform slightly better than a simple reference forecast; demonstrating the value of the ensemble and learning system approach over a single-model forecast;
- Good quality training data, including availability data, are essential. As for the moment, the access to real-time wind plant output data is limited, including curtailments and outages, which will directly influence the accuracy of the forecasts;
- Further experiments are needed in order to obtain a good neural network setup and a good forecast. The biggest potential for further improvements will be in the very short term prediction up to a few hours ahead.

Generally, for time horizons beyond a few hours it is the quality of the input data from the weather models that limits the quality of the wind power predictions. Therefore any error made by metrology is critical for wind power prediction and therefore when wind data input is not accurate, then there will be forecast errors leading to an inaccurate generation prediction. Same principles stand for wind power model accuracy.

4.2 Valid requirements for wind turbines

As most of wind generation is connected to western European countries belonging to *UCTE* and *NORDEL* synchronous areas, the wind turbine installations are developed according to operating standards and grid codes imposed in those synchronous areas. Operating practices and technical rules for power plants connected to the Estonian power system are somewhat different and compliance with these rules is critical in order to maintain operational reliability and security of supply when connecting large amount of wind power [51, 52].

Integration of wind parks into Estonian power system requires the fulfilment of different requirements set by the TSO and Estonian legislation (National Grid Code, Electricity Market Act) [53, 48]. There are several technical requirements which the wind parks must follow when connecting itself into the power networks in Estonia [IV].

Wind turbine should participate in the control tasks on an equal level with the conventional power plants, constrained only by the limitations imposed at any time by the existing wind conditions. Also requirements concerning frequency and voltage variations, active power regulation, FRT, power quality, testing of wind power units and specific instructions for control and automation should be fulfilled [54-56].

The main concern in Estonian case is the wind park FRT capability and stable operation during large frequency and voltage deviations [IV].

If the installed wind turbine is technically adequate to fulfill the electrical grid requirement basis, the success of integration should be guaranteed. Proper FRT capability of wind turbine generators should guarantee the fulfilment of requirements of the Estonian Grid Code.

Another concern is islanding of Estonian power system during large frequency deviation. Estonia power system has a system automation which will disconnect it from all other systems if some type of large disturbance occurs. If the primary reserve is not sufficient at each moment, the islanding is followed by a blackout of the whole system. For that reason the guaranteed operation of all power plants, incl. wind turbines, during temporary low and high voltages is mandatory. In case the wind power forms a large part of generation, the active participation in frequency control is essential for restoring the normal operation.

4.3 Influence of wind power on power quality in weak grid

Currently in Estonia the existing wind turbines are installed to peripheral areas in terms of power grid. The installment of wind turbines in these areas affects normal operation of the existing grid (one-way power transmission) and can cause deterioration or improvement of power quality [XII].

Distribution grid in Estonian rural areas is usually weaker than in the cities and industrial areas. This is usually connected with the impact on voltage quality that the power produced by wind turbines might have and (although more rarely) the thermal restrictions of grid transmission capacity. These restrictions depend on the characteristics of the grid and the wind power installation.

The areas in Estonia with most wind resources are located far from main supply sources and have only 10-35kV grids with low transmission capacity. When wind turbines are connected to the existing distribution grids it should be kept in mind that these grids are initially planned for unidirectional transmission of electric energy. Until presently the opposite direction of wind turbines' capacity and their special characteristics has not been taken into account in the grid development.

When planning the new wind parks, the network conditions and investigation of possible network disturbances should be considered to choose a type of the wind turbine. The power system of the best wind regions of the Western Estonian (incl. Saaremaa island) is weak. In order to guarantee the supply stability of this region, the application of stricter requirements can not be excluded [IV].

To avoid later disagreements between wind park owners and grid operators on connecting wind turbines into weak grid, the field measurements in connection point before giving out the permission for connection should be made.

4.4 Hiiumaa offshore wind park integration possibilities into the Estonian power grid

Continuously increasing percentage of wind power that is integrated into power system is causing additional challenges to system operators all over the world. In several papers [II] and [III], the possibilities of large-scale offshore wind parks integration into Estonian transmission network are observed.

Due to sufficient support to RES, the development of wind power usage has lead to a noticeable contribution to the power supply in Estonia. This has lead to the situation, where an Estonian transmission system operator has given out wind park grid connection proposals more than currently installed generation capacities. This raises a question: how many wind parks can the power system integrate and what will be the expansion costs? With no doubt, such high quantity of wind power integration requires corresponding heavy investments into electrical networks to provide sufficient transmission capacity and ensure the security of supply [II].

Estonian power system is not the best place for wind power integration. There are excellent wind resources available but the power grids in the coastline and islands whit the usually best wind park sites are weak. The same applies for offshore projects. The previous analysis shows that the connection of considerable wind turbine capacity causes extensive network building, addition of sophisticated control and monitoring devices and active and reactive power regulating capability to the wind turbines, installation of gas turbines, reconstruction of primary and secondary regulators of existing thermal generating units, and more intensive and extending co-operation with neighbouring power systems.

While the onshore wind power development in Estonia is quite limited, then large-scale offshore wind park projects will have huge role to play in the near future to fulfill the set targets. Integration of offshore wind power into Estonian power system is becoming more realistic. Therefore, it is important determine the effect of large-scale wind parks to the Estonian power system. In the current thesis Hiiumaa offshore wind park [II] development is analysed.

Hiiumaa offshore wind park is one potential large-scale wind park construction in the near future, with total capacity up to 1000 MW. According to plans, Hiiumaa offshore wind park will be constructed to the open sea at the northwest from Hiiumaa Island (western part of Estonia). Construction of the wind park will take place in several stages, starting in 2014. The period of construction of an open sea wind park of the specified size could be up to three years [II].

There are several alternatives to connect Hiiumaa offshore wind park into Estonian power system and these possibilities are presented in the next chapter. Both, HVAC and HVDC connection options have been analysed. The grid simulations have been carried out using power system simulation tool PSS/E software. For the studies also Estonian power system complete model was used.

4.4.1 Grid connection options for Hiiumaa offshore wind park

Three most reasonable and technically suitable solutions were investigated and possible grid connection options presented in Fig. 4-2.

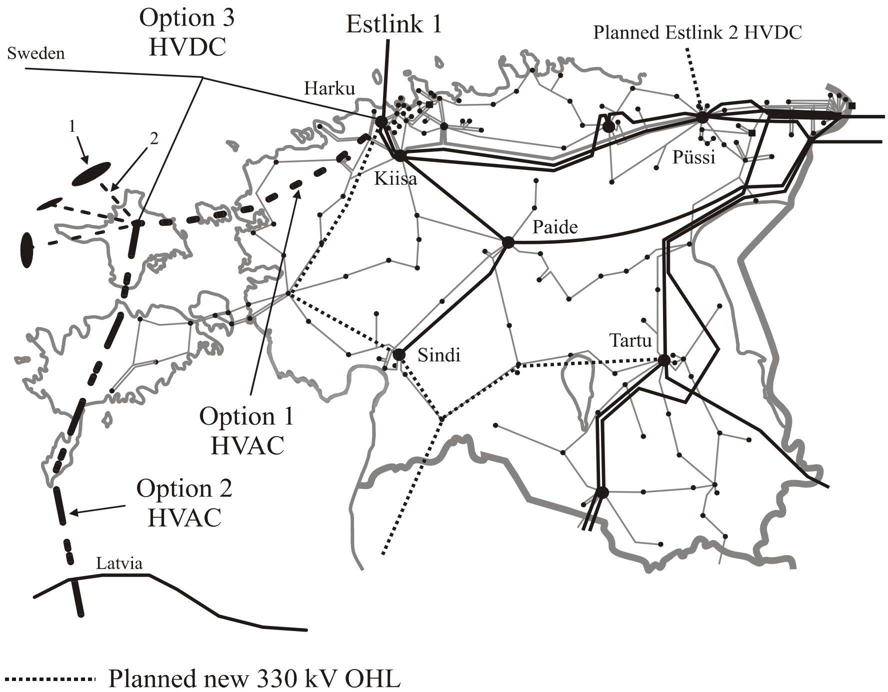

Figure 4-2 Possible connections of Hiiumaa offshore wind park

To describe the different possibilities, it is useful to structure the wind park power transfer system by separating it into three parts. In the first part (In Fig 4-2, binding system - 1), single wind turbines will be connected into unite sections using submarine cables. The network consists of radial and parallel cables lines which all lead from wind turbine transformers to section substation. Voltage level 33 kV is used. The section substations are equipped with step-up 33/110 kV transformer(s) and reactive power compensation devices.

In the second part (from sections to on-land substation - 2) all wind park marine sections are connected into one on-land substation using 110 kV submarine cables. In the substation, power is transmitted to the 330 kV network through 110/330 kV step-up transformers. Due to considerable charging currents in submarine cables, it is essential to install reactive power compensation devices to both substations at the ends of 110 kV cable lines.

Usually the configuration of binding system and transfer system from sections to on-land is slightly affected by different approaches of transfer technology on higher voltage side. In current case studies, it was assumed that the first two parts of wind power transfer system sustain its configuration in case of all different alternative scenarios and the major changes will appear in the third part.

The third part (connection to the transmission grid) has several alternatives. From aspect of technology, transmission of power to the grid could be done using either HVAC or HVDC solution. The determination of sufficient configuration is a complicated optimization task of minimizing construction costs and power losses.

In case of long HVAC submarine cables, it is very important to use reactive power compensation in order to avoid large voltage deviations and decrease active power losses. Considering the cables at different voltage levels there is a limited length of cable line that needs to be equipped with reactive power compensation devices. In some cases, this means that additional marine terminals for compensation must be constructed, for example, it is necessary, in case of HVAC 330 kV cable lines between the Hiiumaa Island and the mainland.

The first case to be investigated was a HVAC connection from Hiiumaa Island to Harku substation (Option 1 in Fig. 4-2). With HVAC technology it is feasible to minimize the cable lengths and to OHL possibility in a maximal way. Despite of that goal, there is one part of the route where cable must be used, because the right of way of the power line must cross the sea and there are also environmental restrictions involved. Analysis showed that in order to avoid voltage rise in the cable and minimize the losses, reactors must be used in the middle of the cable line. Hence, marine platform stations must be constructed. The overvoltage risk is especially high in a no-load regime of wind farm. The total reactive power compensation capacity that must be installed in case of the first case is 590 MVAr.

One alternative of the wind park connection to transmission systems of Estonia and Latvia was analysed (Option 2 in Fig. 4-2). The study showed that in this solution an additional 210 km of 330 kV cable lines and several compensation stations must be built along the cable line. The total amount of reactive power compensation devices in this case reaches up to more than 2000 MVAr.

The third option observed was the HVDC solution from Hiiumaa Island to Harku and possibly to Sweden (Option 3 in Fig. 4-2). Using HVDC transmission is modern and advanced alternative for the third part of wind park transmission system. The main challenge could be the construction of platform converter sub-station with required HVDC terminals. Furthermore, the technology is still rather expensive compared to HVAC transmission, but compared to HVAC technology it does not need so much reactive power compensation and has lots of advantages concerning power flow control in the power line. The study revealed that the HVDC solution is only feasible when the wind park is in addition to Estonian power system also connected to the Swedish power system. In that case a multi-terminal HVDC system shall be used. Next to the power flow control in the wind park it also enables to control power exchange between Estonia and Sweden.

Comparing different connection approaches of HVDC or HVAC technology, the total losses in the wind park transmission system are slightly different. Fig. 4-3 shows the networks losses for all three cases. At high output power from the wind park the active power losses are about equal but in case of low load the advantage concerning active power losses goes to HVAC technology. Reactive power compensation requirements in different cases are shown in Fig. 4-4.

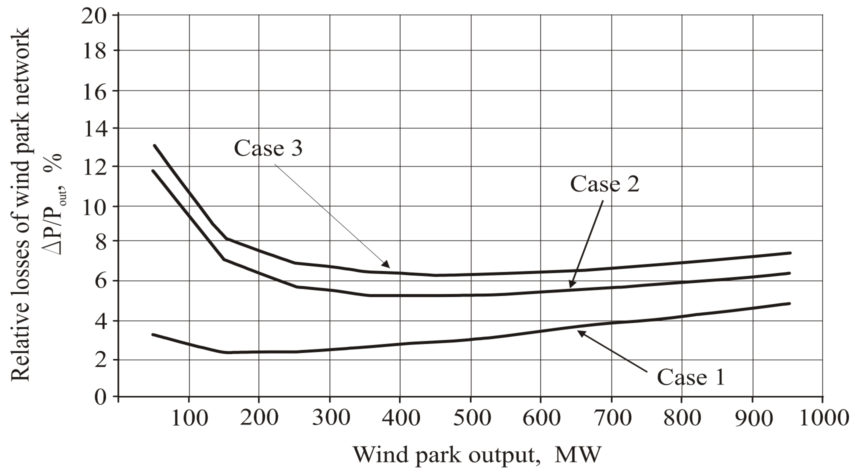

Figure 4-3 Comparison of relative losses in different wind park output power values in different connection cases (Case 1 – HVAC to Harku and Sindi substation, Case 2 – HVAC to Latvia, Case 3 HVDC)

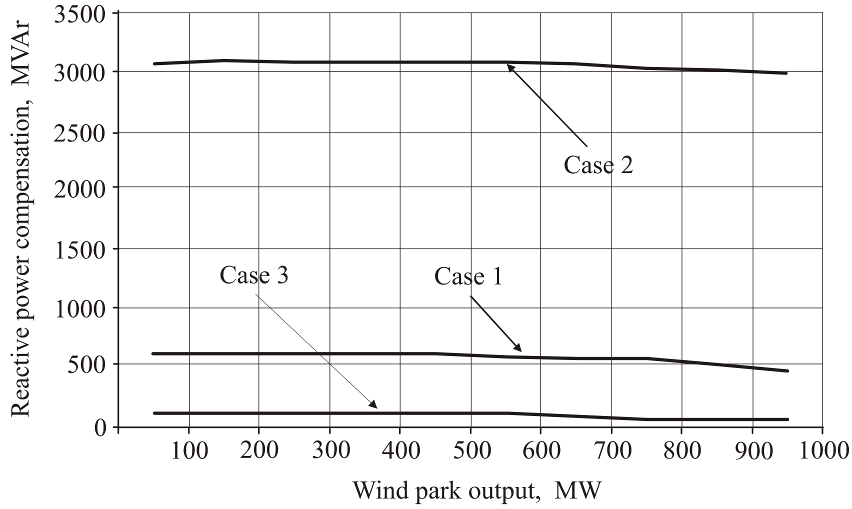

Figure 4-4 Reactive power compensation requirements in different connection cases (Case 1 – HVAC to Harku and Sindi substation, Case 2 – HVAC to Latvia, Case 3 HVDC)

4.4.2 Grid integration costs

In the analysis also the construction cost of the higher voltage (330 kV) part of the grid connection was estimated. It was found that the most feasible solution will be to connect the wind park substation to only the Estonian power system with two 330 kV overhead lines. This was considered a base alternative for comparing and estimating other solutions. In that case the cost of submarine 330 kV HVAC cables from Hiiumaa Island to mainland formed a major part of the total cost of the connection, despite the fact that their length is few times less compared to 330 kV overhead lines.

Proceeding from cost comparison of all alternatives the HVDC solution is on the second place and is estimated to have 14% extra investments compared to base solution. The most expensive alternative is the option when the Hiiumaa wind park will be connected to both Estonian and Latvian 330 kV power systems. The price of that solution was estimated to be 3.7 times more expensive compared to the base alternative. The high price is proceeding from long submarine HVAC cables between Saaremaa and Ventspils and from large reactive power compensation requirements.

In brief, with current Estonian power system configuration, the 1000 MW large-scale wind power integration costs could be approx. 0.67 MEUR/MW, which would cover the construction of the grid connection point, necessary system upgrades and wind park electrical installations as far as grid connected substation.

4.4.3 Summary of the grid integration

Performed power grid and economical calculations showed that the optimal solution for Hiiumaa project is to expand transmission grid through HVAC grid development. The optimal wind park connection basic scheme is shown in Fig. 4-5.

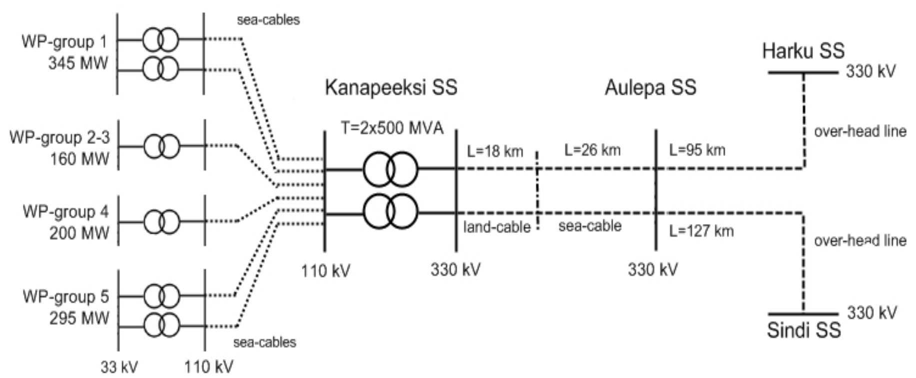

Figure 4-5 Optimal connection solution for Hiiumaa offshore project [II]

The HVDC connection will be reasonable only if there will be another direct HVDC link from Estonia to Nordic market area (Sweden). It is thinkable if under certain market situations the offshore wind power could be attractive for Scandinavian electricity consumers.

In recent years the development of wind power has increased significantly and therefore to uphold Estonian power system security and to accommodate all the possible wind power large amount of investments into the network must be made [II].

4.5 Balancing options for wind power

The system imbalance caused by wind power forecast errors has to be compensated by the generation of schedulable, mainly conventional capacities in the power system. Fluctuations in wind speed can occur quite fast and the resulting problems increase with the amount of installed wind turbine capacity. Fluctuation can result in a steep negative gradient of wind power generation, which has to be compensated by other power plants. Sufficient amounts of reserve capacities have to be provided.

Hardest situation for every power system is a sudden wind power generation drop. This situation is especially tense in Estonia, as the national-territory of Estonia is quite small and distances between different wind park sites are short and the possibility that 80% of installed wind capacity can change rapidly during very short time does exist.

As more wind power is introduced to the power generation system, periods during which thermal power plants in the system are uneconomical to run are becoming more frequent. Whether it is economically advantageous to shut down some thermal plants in such situations, or to keep them running, depends on the length of these periods, the tariff system handling back-up power and possibilities for exporting electricity to other systems.

Currently in Estonia, the balancing the wind parks is only possible through power exchange with the neighboring countries because there are no fast-starting generating units (gas turbine, hydro, etc.) available inside the Estonian power system. Existing large thermal power plants are slow and they are not envisaged for the providing the regulating power. Therefore heavy power compensation is needed. Balance power purchase is currently limited with synchronous system (IPS/UPS). Scandinavian regulating power market can be used by local TSO's only and power from Nord Pool spot market can be bought two hours in advance.

The capacity for wind power is limited with 750 MW (without additional reserves) and it is directly limited by the transmission capacity of existing interconnections and actual power transit. All the wind power development projects which surpass the previous limit must have equal amount of regulating power units guaranteed, before TSO would connect them into the power system. Available regulating power units must be connected into the Estonian power system.

In order to ensure an adequate capacity mix in future time periods (e.g. year 2020) also for the large-scale wind power shares encountered, it is essential that Estonian TSO (the whole BALTSO) will have access to the Scandinavian regulating power market. One substantial presumption here is the availability of sufficient interconnections in the future (Estlink 2, Swedlink).

The main initial conclusions for wind park balancing options in Estonia could be drawn:

- If balancing units must be in the Estonian power system, the energy mix is crucial. The best energy mix: existing Narva thermal power plants, new gas turbines and CHP’s with heat accumulators;
- In other case the Latvian hydro cascade and Lithuanian pumped storage plant (after Ignalina NPP closure) are currently the best available options.

Current potentiality for DSM is quite limited (only 40-50 MW). It would be slightly improved if there will be sufficient smart grid system applications available and skillfully integrated on demand side.

In the near future, there is a good opportunity to build a pumped storage power plant in Estonia. Currently it seems that it could be most optimally achieved jointly with the planned granite mine in Maardu using its emptied caverns. The main advantage in this particular case is the fact it would be easily possible to achieve a considerable gross head between upper and lower reservoir (ca 250 m). Optimal size for such power plant could be 200-400 MW.

4.5.1 Balancing costs

On a 10-20 years time horizon, it is difficult to predict the cost of balancing as well as the market value of wind power. But this is usually the era where potential investors seek answers before making the investment decision.

When tracking up current balancing prices in Estonia, we can witness that during 2006-2009 there where periods when upward regulation price was already more than 1200 EEK/MWh. According to Nordic Power Management OÜ (NPM), average sale price in 2008 was 556.47 EEK/MWh and average purchase price was 530.86 EEK/MWh.

It can be predicted that in the future the magnitude of the readiness for upward and downward regulations will depend on the magnitude of the spot market price. If the sport price is low, the readiness premium for upward regulation is higher, than the readiness premium for downward regulation. However, when spot price is higher the readiness premium for downward regulation will be higher than premium for upward regulation.

Therefore, if there will be considerable amount of wind power (700-1000 MW) eventually installed into the Estonian power system and wind variability remains high or wind power forecast accuracy, will not improve, the amount of required regulation power is likely to be quite high, which means greater impact on the price of up-regulation. The future market prices will be determined by the generation cost of the most expensive generating unit available in the system.

In brief, there are lots of uncertainties involved when calculating the balancing price formation for the future. These are:

- fuel prices, CO_2 price etc;
- conception of future electricity market and market prices
- indistinct usage of interconnection;
- actual availability of power system reserves;
- transmission costs.

Rough estimations for prices of different balancing units are given in Table 4-2.

Table 4-2 Approximate estimations for possible reserve costs and for total costs of wind turbine and balancing unit

Regulating option	Reserve cost, EUR/MWh	Total cost of wind turbine (65 EUR/MWh) and reserve unit
Oil-shale plant	30	95
Gas turbine	25	90
Hydro/pumped storage	25-40	90-105
From balancing market	75-100	140-165

5 AN OPTIMAL MODEL FOR BALANCING FLUCTUATING POWER OF LARGE WIND PARKS

5.1 Unit commitment and scheduling

The problem of optimal planning of generating units (OPGU) arises in optimal operation of the power system as well as planning the new units for expanding power system. This is one of the most important optimization problems in the power system.

The OPGU problem is dealt with as a two-stage problem: 1) optimization of dispatching and 2) optimization of unit commitment [57].

The optimal dispatch problem is interrelated with unit commitment and incompleteness of information (taking into account the emission taxes and also probabilistic, uncertain and fuzzy information) [58].

In addition to optimization of load distribution between working power units, a very important problem is the optimization of working unit's combination for every hour. This problem is known as unit commitment problem [33].

The unit commitment problem in the power system is to find commitment schedule and the operating level of all generators (units) at each time in each day in order to minimize the total fuel cost. This minimization is done under various constraints. For example, the total output power at each time must meet demand anticipated over a given time horizon.

The unit commitment is a problem of determining the optimal schedule of generating units subject to the technical and operating constraints.

The unit commitment schedules are determined in the assumption that load distribution between working units is optimized.

The unit commitment problem is a mixed integer nonlinear programming problem and is usually set up on power systems level. Nevertheless, the optimization of the unit commitment schedules gives the great economical effect also in the power plant level. There are numerous methods developed for electric power scheduling.

The main methods used for optimizing the unit commitment schedules are [33]:

- Priority-list methods (incl. branch and bound method);
- Dynamic programming methods;
- Discrete programming methods;
- Lagrange relaxation method.

The priority-list methods are the most popular. The Lagrange relaxation method has gained popularity during the recent years.

The Lagrange relaxation method is to obtain indirectly the primal solution by solving the dual problem, while the others methods directly solve the primal problem. The dual problem can be decomposed into single generator problems. Lagrange methods have potential to solve large-scale problems and handle large number of constraints.

The generation scheduling is broken down in long-term (3-5 years ahead), medium-term (1-2 years) and short-term (1week) scheduling [59].

In deregulated environment the generating company has in principle no other objective than to produce electricity and sell with maximum profit.

As long as the objective is the expected profit, the scheduling can be done as if all generation is sold on the spot market.

The common scheduling models are based on a price taking assumption. The price forecasting is therefore a crucial activity in the scheduling process.

The spot price depends on several factors. In Scandinavia, in the power exchange Nordpool, the most important factor is the amount of stored water in the total system, as there is a dominant hydro generation in the system. Since storage varies slowly, the spot price has a strong sequential correlation.

Generally speaking, the purpose of the short-term scheduling is to optimally match supply and demand in the near future while adapting to the longer term strategies for system operation.

The short-term model gets its boundary conditions from a medium-term model. The time resolution of the medium-term model is one week and the short-term model must connect the time intervals where the boundary conditions are available.

An important consideration in the generation of scheduling and operating reserve assessment is the determination of the regulating margin and the ability of the system to respond to unforeseen load changes and sudden generation outages.

5.2 The impact of wind power on power generation scheduling

The variability of wind power impacts on how the conventional capacity is run and how the variations and prediction errors of wind power change the unit commitment [6, 13]. Large variations in wind power output can result in operating conventional power plants less efficiently [7].

In the short-term scale of unit commitment (4…24 h), the wind power can cause extra costs for the system, if the operation of the power plants is made more inefficient due to varying wind power generation and prediction errors. Day-ahead predictions are required in order to schedule the conventional units.

Wind power forecasting is great value for the improved scheduling of wind power and such forecasts can have substantial value even if they are not perfectly accurate [I, VI]. Using physics-based forecasting models, real-time wind and generation data from the wind parks, and computational learning systems such as artificial neural networks, it is possible to provide forecasts of wind power delivery that are significantly better than simplistic forecasts based on climatology or persistence [8].

5.3 Optimization of Power Plant Operation

Current work describes the short-term generation scheduling model for balancing fluctuating power of large wind parks in the Estonian power system.

Estonia was used as a reference and the proposed model could be successfully used in other similar power systems which include mainly thermal power plants.

Clearly, the most important problem here is how to balance the mistakes made in the wind-park load forecasting. The options discussed hereafter for balancing forecast capacity errors for wind parks are:

- Usual oil-shale burning thermal power units;
- Gas turbines (natural gas);
- Pumped storage power plant.

The optimal balancing consists of two problems:

- Optimal unit commitment;
- Optimal load dispatch between operating power units in power plant (in power system).

Initial data: The input-output characteristics of power plants:

$C^{Th}(P^{Th})$ – cost characteristic of oil-shale burning thermal power unit, EUR/MWh

$C^{GT}(P^{GT})$ – cost characteristic of gas turbine (fuel – natural gas), EUR/MWh

$W^{PH}(P^{PH})$ – cost characteristic of pumped-storage hydro power plant, m^3/s per MW.

5.3.1 Basic formulation for short-term generation scheduling

The optimal dispatch problem is to determine the loads of power units so that the total generation cost in 24-hours time period is minimized and all constraints are met. The block scheme of possible short-term generation scheduling optimization is presented in Fig. 5-1.

The goal is to minimize the following objective function:

$$\min C = \sum_{t=1}^{24} \left[C_t^{Th}(P_t^{Th}) + C_t^{GT}(P_t^{GT}) \right] \quad \textbf{(3)}$$

subject to power balance equations:

$$\Delta P_t^{WP} - P_t^{Th} - P_t^{GT} - P_t^{PH} = 0, \quad t = 1,\ldots,24 \quad \textbf{(4)}$$

hydraulic constraint:

$$\sum_{t=1}^{24} W^{PH}(P_t^{PH}) = 0 \quad \textbf{(5)}$$

thermal power unit's (Th) generation limits:

$$P_{\min}^{Th} \le P_t^{Th} \le P_{\max}^{Th}, \quad t = 1,\ldots,24 \quad \textbf{(6)}$$

gas turbine's (GT) generation limits:

$$P_{\min}^{GT} \le P_t^{GT} \le P_{\max}^{GT}, \qquad t = 1,\ldots, 24 \tag{7}$$

pumped storage hydro power plant's (PH) generation limits:

$$P_{\min}^{PH} \le P_t^{PH} \le P_{\max}^{PH}, \qquad t = 1, \ldots, 24 \tag{8}$$

pumped storage hydro power plant's pumping load limits:

$$P_{\max}^{PH-} \le P_t^{PH} \le P_{\min}^{PH-}, \qquad t = 1,\ldots, 24 \tag{9}$$

The Lagrange function of the problem is following:

$$\Phi = \sum_{t=1}^{24}\left[C_t^{Th}(P_t^{Th}) + C_t^{GT}(P_t^{GT}) + \mu_t \cdot (\Delta P_t^{WP} - P_t^{Th} - P_t^{GT} - P_t^{PH})\right] +$$

$$+ \lambda \cdot \sum_{t=1}^{24} W^{PH}(P_t^{PH}) \tag{10}$$

where μ and λ are Lagrange multipliers.

The reservoir constraints are to be monitored in the computational procedure.

Here

P_t^{Th} – power generation of thermal power unit in time interval *t*

P_t^{GT} – power generation of gas turbine in time interval *t*

P_t^{PH} – power generation of pumped-storage hydro power plant in time interval *t* ($P_t^{PH} < 0$, when power plant operates as a pump and $P_t^{PH} > 0$, when power plant act as generator)

W_t^{PH} – amount of water discharge by generating electricity ($W_t^{PH} > 0$) or pumping in reservoir ($W_t^{PH} < 0$) in time interval *t*, m^3/h

ΔP_t^{WP} – wind power generation forecasting mistake in time interval *t*, $\Delta P_t^{WP} = P^{WP,F}{}_t - P_t^{WP}$

"min" and "max" mean the minimum and maximum values of the parameters.

Storage reservoirs have limited storage capability and pumped-storage plants may be operated on a daily or weekly cycle. In the present case, the pumped storage power plant operates on a daily cycle.

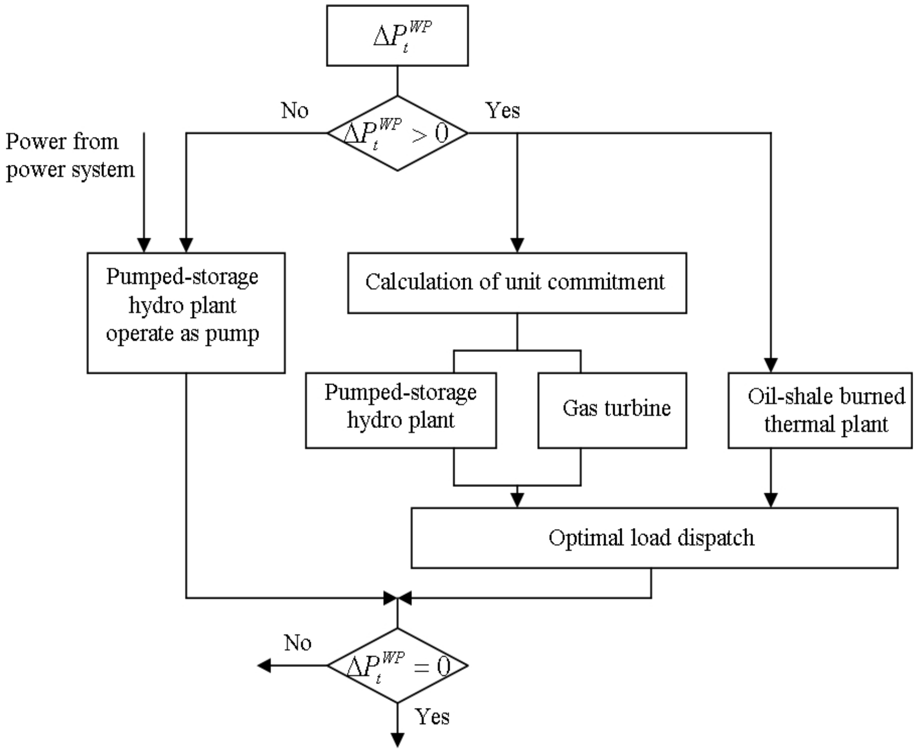

Figure 5-1 Block scheme for generation scheduling optimization for 24-hour time period

The conditions for the optimum of values P^{Th} , P^{GT} and P^{PH} are:

1) for thermal power unit:

$$\frac{\partial \Phi}{\partial P_t^{Th}} = \frac{\partial C^{Th}(P_t^{Th})}{\partial P_t^{Th}} - \mu_t = 0, \qquad t = 1,\dots,24 \tag{11}$$

2) for gas turbine:

$$\frac{\partial \Phi}{\partial P_t^{GT}} = \frac{\partial C^{GT}(P^{GT}{}_t)}{\partial P_t^{GT}} - \mu_t = 0, \qquad t = 1,\dots,24 \tag{12}$$

3) for pumped-storage hydro power plant:

$$\frac{\partial \Phi}{\partial P_t^{PH}} = -\mu_t + \lambda \cdot \frac{\partial W^{PH}(P_t^{PH})}{\partial P_t^{PH}} = 0, \qquad t = 1,\dots,24 \tag{13}$$

4) for determination the Lagrange multipliers:

$$\frac{\partial \Phi}{\partial \mu_t} = \Delta P_t^{WP} - P_t^{Th} - P_t^{GT} - P_t^{PH} = 0 , \qquad t = 1,\dots , 24 \qquad \textbf{(14)}$$

$$\frac{\partial \Phi}{\partial \lambda} = \sum_{t=1}^{24} W^{PH}(P_t^{PH}) = 0 \qquad \textbf{(15)}$$

The optimal solution of the problem **(3)–(5)** must satisfy the conditions **(11)–(15)** and constraints **(6)–(9)**.

The unit commitment problem can be solved using the Lagrange multipliers iteration method or incremental cost method. The Lagrange multipliers iteration method is an iterative method, where optimal solution to the optimization problem is found by solving necessary optimality conditions. Here, the optimal values of Lagrange multipliers μ and λ are selected in iterative way.

The calculation is carried out as iterative procedure:

1. Set initial values of Lagrange multipliers μ_{t0} (t = 1, 24), λ_0 and permitted tolerances ε_P and ε_W.
2. Set $\lambda = \lambda_0$.
3. Set t =1 and W = 0.
4. Set $\mu_t = \mu_{t0}$.
5. Calculate optimal values of P_t^{Th}, P_t^{GT} and P_t^{PH} from the equations (9) – (11).
6. Check limits (4) – (7) of generating/pumping powers and if necessary, correct the calculated optimal values of P.
7. Check power balance $\Delta P = \Delta P_t^{WP} - P_t^{Th} - P_t^{GT} - P_t^{PH}$:
   $|\Delta P| \le \varepsilon_P$
   If "Yes" $\rightarrow$ point 9
   If "No" $\rightarrow$ point 8.
8. Correction of the value μ_t:
   $\mu_t = \mu_t + S_P \cdot \Delta P$
   where $S_P > 0$ is a correction step.
   Proceed to point 5.
9. Calculate $W = W + W_t$
   Set $\mu_{t0} = \mu_t$, $t = t + 1$

If $t \leq 24$, then proceed to point 4.

10. Check water balance:
$|W| \leq \varepsilon_W$
If "Yes" $\rightarrow$ point 12
If "No" $\rightarrow$ point 11.

11. Correction of the value λ:
$\lambda = \lambda + S_W \cdot W$
where $S_W > 0$ is a correction step.
Proceed to point 3.

12. The end.

On the same time the unit commitment problem is solved. When the optimal value of power remains under minimum load of the power plant, the power generation in gas turbine and pumped storage power plant is 0, i.e. the plant is out of operation.

The methodology described above was realized in an MS EXCEL program (customized in TUT, at the Department of Electrical Power Engineering).

5.3.2 The reference scenario

The examined scenario presumed that there is 1000 MW of wind power installed into the power system. Wind power forecast error is taken 35% and it is presumed that only errors from over forecast of wind power generation should be balanced. The situation when wind power output is more than predicted has not been analysed here as this is not so crucial for system operator and there are several options to solve it (e.g. electricity export or downward regulation).

The input-output characteristics of balancing units are given in the form of square polynomial functions $C(P) = a_0 + a_1P + a_2P^2$ (Table 5-1).

Gross head of pumped storage power plant is taken h = 28 m = const. Reservoirs volume of pumped storage hydro power plant is 6 000000 m^3, the initial and final volumes are 3 100 000 m^3.

Table 5-1 Cost characteristics of three generating units (Th, GT and PH)

Unit, cost	a_0	a_1	a_2	P_{min}, MW	P_{max}, MW
Thermal, EUR/MWh	427,79	22,22	0,00062	70	180
GT, EUR/MWh	1489,99	41,66	0,07526	9,6	96
HP (generating), m^3/s	10,274	5,1	0,021	12	100
HP (pumping), m^3/s	0,274	3,99	0,009244	-12	-100

Examples of generating unit's input-output characteristics are presented in Fig. 5-2 and in Fig. 5-3.

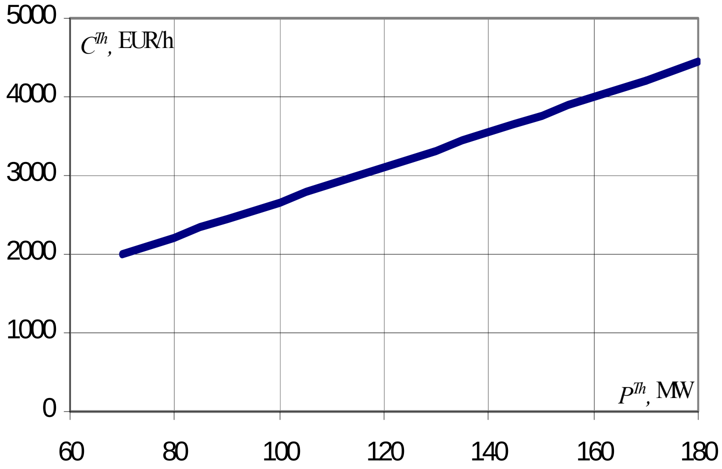

Figure 5-2 Fuel cost characteristic of thermal unit

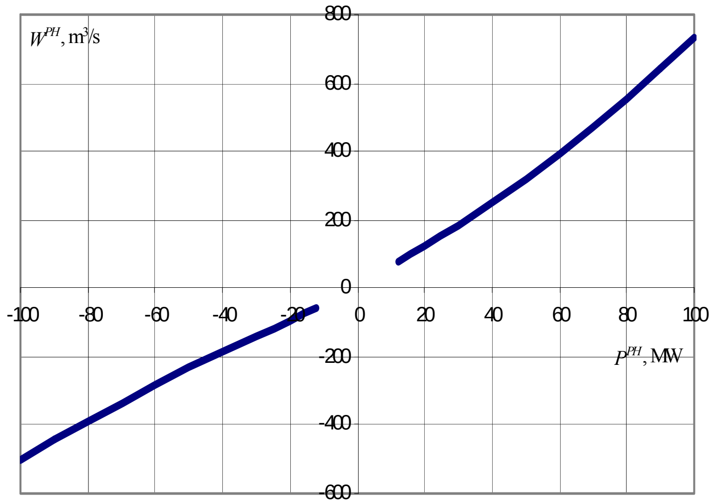

Figure 5-3 Water cost characteristic power generation of pumped storage hydro power plant

5.3.3 Results

Wind power generation forecasting error ΔP_t^{WP} in used calculation is set value and variable in power interval 80–350 MW (Table 5-2).

Results of calculation of optimal unit commitment and load distribution are seen in Table 5-2, where error and unit loads are given in MW, reservoir volume and used amount of water discharge is given in thousands of cubic meters (m^3), and fuel cost is calculated according to values given in Table 5-1 and presented in EUR.

Table 5-2 Results of the calculation

Hour	ΔP_t^{WP}	P^{PH}	P^{Th}	P^{GT}	Volume	W^{PH}	$\sum_{t=1}^{24} W^{PH}$	Fuel cost
1	200	0,0	180,0	20,1	3100	0	0	6806
2	200	0,0	180,0	20,1	3100	0	0	6806
3	200	0,0	180,0	20,1	3100	0	0	6806
4	300	45,3	180,0	74,7	2076	1024	1024	9472
5	300	45,3	180,0	74,7	1052	1024	2048	9472
6	300	45,3	180,0	74,7	28	1024	3072	9472
7	100	-55,8	155,7	0,0	971	-943	2129	3903
8	100	-55,8	155,9	0,0	1914	-943	1186	3907
9	100	-55,8	155,8	0,0	2857	-943	243	3906
10	80	-56,0	135,9	0,0	3804	-946	-704	3458
11	80	-55,9	136,0	0,0	4750	-946	-1650	3461
12	80	-55,9	136,0	0,0	5697	-946	-2597	3461
13	190	0,0	180,0	10,1	5697	0	-2597	6366
14	190	0,0	180,0	10,1	5697	0	-2597	6366
15	190	0,0	180,0	10,1	5697	0	-2597	6366
16	350	74,0	180,0	96,0	3888	1809	-788	10631
17	350	74,0	180,0	96,0	2079	1809	1021	10631
18	350	74,0	180,0	96,0	270	1809	2830	10631
19	200	0,0	180,0	20,1	270	0	2830	6804
20	200	0,0	180,0	20,0	270	0	2830	6802
21	200	0,0	180,0	20,0	270	0	2830	6801
22	100	-55,8	155,7	0,0	1213	-943	1887	3903
23	100	-55,8	155,8	0,0	2157	-943	943	3906
24	100	-55,8	155,8	0,0	3100	-943	0	3906

According to these calculations, the error for 24 hours in case for installed 1000 MW wind park is 4560 MWh. Most of the balancing is made in the thermal power plant (4042 MWh) followed by the gas turbine (662 MWh). In 24 hour period, the pumped storage power plant produces 358 MWh and uses 144 MWh of electricity to fulfil the upper reservoir. Total fuel cost of the presented generation operation is 154 042 EUR.

5.3.4 Concluding remarks

Oil-shale thermal power plant does not match well for covering forecast errors in wind park generation, because it's manoeuvring ability is limited, it cause higher fuel consumption (high start-up cost) and there are lots of uncertainties involved (e.g. mining volumes, environmental taxes) what will strongly influence the balancing costs in the future.

Surface relief in Estonia does not apply well for pumped storage power plant. It is considerable option only then, if there will be artificially constructed gross head between upper and lower water reservoir (ca 150-200 m). Therefore the conception to build power plant into the planned granite mine seems technically reasonable option. Notable feasibility could be gained with the availability of NPP in the system. Power plant working in pump-regime would give needed base load for NPP during the night, when electricity price is remarkably cheaper than during the day. Also there is always option to use over generation of wind power for pumping storage or for direct electricity storage (e.g. different types of batteries).

The perspective of the gas turbine is directly connected with the future of the natural gas price and security of gas supply.

In brief, for solving the problems related to the unit commitment and optimal load dispatch, mathematical optimisation methods should be used. Only then the optimal solution could be achieved guaranteeing the minimum fuel cost for the entire power system.

6 LARGE-SCALE WIND POWER INTEGRATION OPTIONS FOR ESTONIAN ENERGY SYSTEM TROUGH LONG-TERM PLANNING

6.1 Long-term energy sector planning under uncertainty

Energy planning consists of energy system development, systematic analysis, estimation and formation. It includes establishment of objectives, strategy determination and the achievement of objectives. Energy planning objectives are energy supply adequacy, security, economic efficiency and environmental-social acceptability [47].

Energy systems analysis can be used at several levels in the decision-making process, from the formulation of the political agenda to the day-to-day operation of generating units. Investments in energy technology usually have long lead times and a long life span. The consequences of different developments of the energy system must be evaluated over a long time period (25-40 years). Within this time horizon, the uncertainties of the developments in the system environment greatly influence the cost-efficiency of different technological options. The treatment of these uncertainties is one of the key issues in the energy planning process.

Variations in load factors, spot prices of energy carriers, and in the availability of energy generating units play an important role in the daily and seasonal planning for the operation of the energy system. These variations are examples of static uncertainty, and can be handled by, for instance, stochastic or dynamic programming approaches [60].

The long term analysis of the energy system is fraught with uncertainties, be it the specification of demands and prices, or the availability and characteristics of future technologies, or the emission targets that should be adopted [61, 62].

In the decision making under uncertainty, the decision criteria are based on the decision maker’s attitude toward life. The criteria include the:

- maximin criterion - pessimistic or conservative approach;
- minimax regret criterion - pessimistic or conservative approach;
- equally likely, also called LaPlace criterion - assumes that all probabilities of occurrence for states of nature are equal;
- maximax criterion - optimistic or aggressive approach;
- principle of insufficient reasoning – no information about the likelihood of the various states of nature.

Different long-term energy sector planning approaches are closely reviewed in Mart Lansberg’s PhD thesis [47] which was defended in TUT in winter 2008.

6.2 Energy system planning using models

An effective assessment of energy-related policy instruments requires the use of models capable of simulating the technological change necessary to induce long-term economic shifts towards a sustainable energy system, while simultaneously representing in adequate detail the key energy-economy-environment interactions.

It is necessary that the energy system planning must be optimal. Therefore, both in the short and long perspective, we must ensure that the security of supply, reliability, use of resources, environment indexes, consumption, etc. are all optimal.

Important planning task input data are [IX]:

- Existing energy system description (Reference Energy System);
- Base year energy balance;
- Planning period and base rate;
- Beneficial energy demand forecast according to economic progress scenario;
- Technology lifetime, technical shape and spending prognosis;
- New possible technologies and existing reconstruction;
- Primaries-energy resources and limitations;
- Fuel prices forecast;
- Environmental limits – taxes;
- Socio-economic limits.

Simple etalon energy system example is showed in Fig. 6-1.

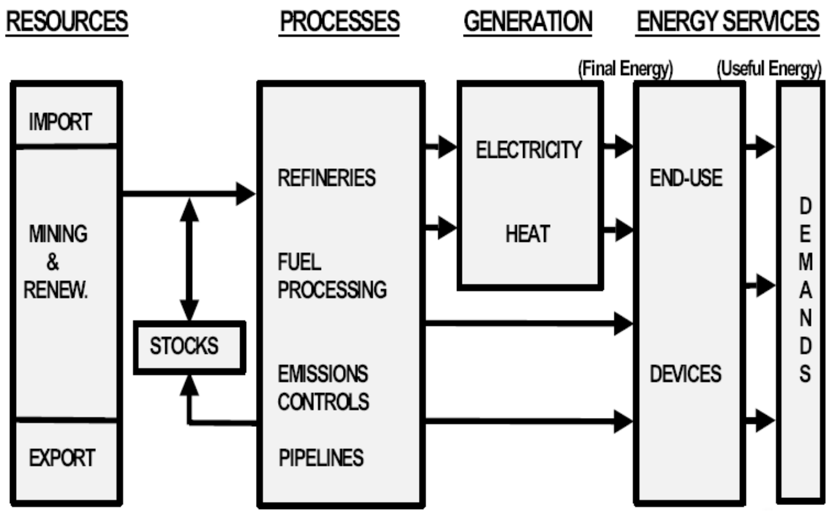

Figure 6-1 Reference Energy System [IX]

Reference Energy System describes itself as a scheme where, in the buses, there are included all substantively existing and future system energy resources, processes, transformation technologies, electricity networks, cleaning procedures, consumer durables, economy measures, beneficial energy consumption etc. and this is all consolidated by a corresponding power flow. Reference Energy System shows us all possible primary energy flows through different transformation processes up to all energy customer-services.

The development of the concepts of linear and nonlinear optimization models presumes that all of the data for the optimization model are known with certainty. However, uncertainty and inexactness of data and outcomes pervade many aspects of most optimization problems. As it turns out, when the uncertainty in the problem is of a particular (and fairly general) form, it is relatively easy to incorporate the uncertainty into the optimization model.

6.2.1 Energy system planning models

There are many different energy system-planning models used today (integrated resource planning models, integrated energy-economy-environment optimization models, etc.) and they are introduced in [IX].

In Estonia, MARKAL; MARKAL-MACRO; MEDEE-N and EnergyPro models are in use at Tallinn University of Technology, Department of Electrical Power Engineering.

The long-term system planning analysis results presented in chapter 6.6 has been carried out using the Estonian MARKAL model [V, 47, 63].

6.2.2 MARKAL model

MARKAL, an acronym for *MARK*et *AL*location, is a dynamic linear programming (LP) "bottom-up" model, which finds the optimal development of the energy system in time under given technology characteristics and boundary conditions. MARKAL represents the current and potential future technology alternatives through the so-called Reference Energy System. The MARKAL model is a generic technology-oriented model tailored by the input data to obtain the least-cost energy system configuration for a given time horizon under a set of assumptions about end-use demands, technologies and resource potentials. It represents the time evolution of a specific Reference Energy System at the local, national, regional, or global level [V, 64, 65].

The MARKAL models [V, IX, 47, 63] allow a wide flexibility in representation of energy supply and demand technologies, and are typically used to examine the role of energy technologies under specific policy constraints, e.g. CO_2 mitigation, local air pollution reduction, etc.

MARKAL (Fig. 6-2) allows a detailed description of existing and alternative energy technologies and existing and alternative paths of energy carriers from their source through different conversion technologies until the point of final use. The MARKAL structure makes it possible to build in supply curves of technical conservation. In most applications, the end use demands are fixed, and a cost-efficient solution is obtained by minimising the energy system's costs over the whole studied period. Basically, MARKAL takes exogenously supplied energy demand figures and determines the optimal energy supply and end-use-device network which can meet the demand. For a feasible solution, the demand must be met in each period. The exact nature of an optimal solution depends both on the criterion of optimality and the ensemble of technological and economic data supplied by the user to characterise country's energy technologies. The existing energy system is described in detail, together with alternative technologies and flow paths in [47].

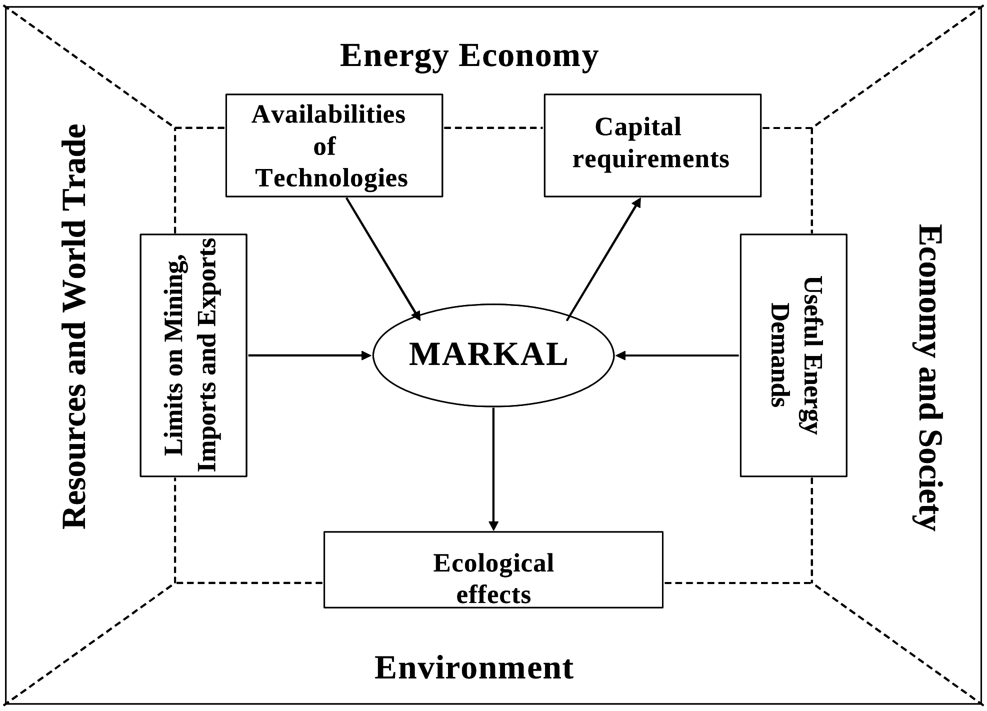

Figure 6-2 MARKAL model

The computation of the MARKAL partial equilibrium is equivalent to the optimization of a suitably constructed mathematical program. A mathematical optimization program is defined as the minimization (or maximization) of an objective function, subject to constraints. If all the mathematical expressions representing the objective function and the constraints are linear, the problem becomes a Linear Program, which may be solved via standard LP optimizers.

6.2.3 Minmax model

The best criterion for electricity generation capacity optimization is the minmax regret criterion [57, 66]. The minmax regret criterion is named the criterion of minmax regret or risk caused by uncertainty of information. The minmax criterion fits both a pessimistic and a conservative decision-maker approach. The payoff can be based on lost opportunity, or regret [47].

$$\min_{\overline{P}(t)} \max_{Z(t)} \int_0^T R(\overline{P}(t), \widetilde{Z}(t))dt \tag{16}$$

where *R* – function of risk or regret caused by uncertainty factors:

$$R(\overline{P}(t), \widetilde{Z}(t)) = C_\Sigma(\overline{P}(t), \widetilde{Z}(t)) - \min C_\Sigma(P(t), \widetilde{Z}(t)) \tag{17}$$

$\overline{P}(t)$ – vector of planned load duration curves of units;

$\widetilde{Z}(t)$ – vector of uncertain factors;

C_Σ – actual total costs of power units;

$\min C_\Sigma$ – minimum of total costs if we could have the exact deterministic information about uncertainty factors.

Operator minmax *R* means the minimization of maximum regret or risk caused by uncertainty factors.

Optimality conditions

The optimality conditions of a minmax problem arise from the main theorem of game theory and can be expressed as follows [67]:

If the $\left(\overline{P}^0(t)\right)$ is the optimal plan for min max *R* criterion, then:

$$R\left(\overline{P}^0(t), Z^-(t)\right) = R\left(\overline{P}^0(t), Z^+(t)\right) \tag{18}$$

In a general case, it is necessary to solve the problem

$$\min_{\overline{P}(t)} \max_{\Omega} \int_0^T E\ R(\overline{P}(t)\ , \widetilde{Z}(t))dt \tag{19}$$

Where:

E – expected value of risk or loss of opportunity;

Ω – a set of mixed strategy of uncertain factors.

It is possible to compose the deterministic equivalent of the minmax problem on the basis of the conditions given above. It requires finding the minmax load demand curves and cost functions of technologies and environmental constraints and taxes. If we replace the deterministic data by the minmax input data, we can use the initial deterministic model for calculating the minmax optimal results [47].

6.3 Long term energy generation planning with MARKAL under uncertain conditions

Generation expansion planning is an important planning problem for the power systems. In the models of integrated energy-economy-environment planning like MARKAL [68] which is used in Estonia [69, 70], the long-term planning of electricity generation capacity is based on the requirement to fulfil the electricity consumption forecast.

Minmax optimization models enable us to take into account the uncertainty of uncontrollable factors and to minimize the maximum possible economic loss (regret) caused by uncertainty.

Therefore, the objective of long-term optimization of electricity generation capacity is the minimization of total costs (expected investment and operational costs) considering the reliability and environmental constraints.

The main sources of uncertainty, uncertainties of energy demand and technology data are closely described in [IX].

The shortened task of optimal long-term planning of electricity generation capacity considering uncertainty intervals will be tackled. A theoretical minmax approach to the problem will be given.

6.4 Basic modelling assumptions

The basic assumptions considered in all the investigated scenarios are presented in [V]. As there are some changes foreseen from the premises used previously, the following assumptions were modified:

- Estonia will not use old pulverized combustion oil shale power plants after 2015 without additional flue gas cleansing devices, in accordance with the schedule agreed with the EU. As a result, only 2 refurbished fluidized-bed combustion units can operate after 2015, and other units must be equipped with flue gas cleansing devices or closed;
- Imported fuel prices are according to estimates of IEA World Energy Outlook 2007 [71];
- Planning period is 2005-2035 and discount factor is 0.05;
- Wind power magnitude in the system power balance reaches 1000 MW by the year 2020;
- There will be 1000 MW of gas turbines installed for securing the power system reserves and balancing wind power fluctuations by the year 2020;
- There is a 200 MW of pumped storage power plant foreseen by the year 2015 and another 200 MW in year 2020.

Options for power generation in Estonia until 2035 are presented in Table 6-1. Fossil-fuel price assumptions are showed in Table 6-2.

Table 6-1 Options for power generation until 2035, MW

	2005	2010	2015	2020	2025	2030	2035
Eesti PP, old boilers	1120	1120	1120	800	0	0	0
Balti PP, old boilers	450	450	450	450	0	0	0
Eesti PP CFBC unit	190	190	190	190	190	190	190
Coal condensing				500	1000	1000	1000
Oil-shale supercritical CFBC, new					600	1200	1200
Oil-shale CFBC, new			300	600	600	1200	1200
Pulp and Paper			74	74	74	74	74
Hydro	15	15	15	15	15	15	30
Pumped storage			200	400	400	400	400
Gas, combined cycle			200	400	400	400	400
Gas, gas turbine		100	200	1000	1500	2000	2000
Iru CHP, existing unit 2	90	90	90	90	90	90	90
Iru CHP, existing unit 1	60	60	60	60	60	60	60
Kohtla Järve CHP, existing	19	19	0	0	0	0	0
Ahtme CHP, existing	20	0	0	0	0	0	0
Balti PP CFBC unit	180	180	180	180	180	180	180
Peat and biomass CHP	0	50	200	200	200	200	300
Wind, onshore	30	140	400	400	400	400	400
Wind, offshore			400	600	600	600	600
Total installed*	**2174**	**2399**	**3779**	**5359**	**5709**	**8009**	**8124**

*Under different conditions (during maintenance, grid limitations and under power transit, etc.) the available capacity could be much lower than total installed.

Table 6-2 Fossil-fuel price assumptions [71]

		2006	2010	2015	2030
oil	$/barrel	62	65	71	108
coal	$/ton	63	62	70	106
gas	$/Mbtu	7.3	7.3	8.2	12.7
oil	EUR/GJ	9.3	11.2	12.2	18.6
coal	EUR/GJ	2.3	2.5	2.8	4.2
gas	EUR/GJ	6.1	7.0	7.8	12.1
oil-shale	EUR/GJ	1.38	1.38	2.37	2.37

The current CO_2 prices (June 2009) sweep between 13-15 EUR/ton, and it is foreseen that the CO_2 price in emission trading could reach the 75EUR/ton level in 2020. Currently the forward arrangements in carbon markets for year 2014 has been with in the price range of 40 EUR/ton [72, 73].

The primary energy resources of Estonia are estimated as follows [V, 70]:

Oil shale – Active resources of the deposit are ca 1,2 Gt and passive resources 4 Gt. The latest research results of the Mining Department of TUT estimate that the resources will last 60 years under current level of exploitation.
Wind – theoretically a very large resource, but its use involves several restrictions [74, 75]. Considering the possibilities of the Estonian power system alone to integrate the wind turbines, the capacity limit is ca 750 MW, which corresponds to the annual generation of 1,6 TWh/year = 6 PJ/year. Maximum long-term annual utilization of wind energy is estimated at 9 PJ/year (requires 1000 MW of installed capacity of wind turbines).
Peat – total deposits 775 Mt (annual limit for extraction is 2.78 Mt/year = 31 PJ/year, annual growth is 0.5 Mt/year = 5.6 PJ/year.
Biomass and waste – theoretical total annual resources are 102 PJ, economically feasible annual resources for CHPs are 21 PJ.
Hydro – the potential is 30 MW (corresponds to the annual generation of 0.5 PJ/year).
Solar – the estimates of annual utilization vary in a wide range: from 0.5 to 8 PJ/year.
Geothermal – in principle 0, only ground heat pumps can be used.

All other fuels have to be imported. The existing natural gas pipelines can supply up to 70 PJ/year.
Coal and oil products can be imported via rail and harbours.

Wind power behaviour is modelled by extrapolating the current wind park hourly production in Estonia [I] and using the information collected from offshore wind parks in Denmark (Horns-Rev, Nysted). Here it is also assumed that, due to geographical distribution, a significant smoothing effect will take place in the future.

It should be mentioned here that the MARKAL model cannot describe the electricity sector in the required detail, thus additional analysis is needed for balancing issues and the accommodation in the power grid (incl. disturbance reserve).

Forecasts of final energy consumption are presented in [V]. The forecasts of population and GDP used in the modelling are presented in [V, VIII, X, 47, 63].

6.5 Scenarios

Scenarios are developed here according to the possible capacities of wind parks, possible developments of CO_2 price and possible development of conventional generation.

The main uncertainties relating to wind park are related to the capacity of the wind park, input characteristics such as capital cost, and the balancing costs of the wind park.

The main uncertainties in connection with CO_2 are related to the price of CO_2 in emission trading.

The main uncertainties with the development of renewable intermittent generation are related to large-scale wind power development in Estonia.

These scenarios assume that other parameters such as load growth and fuel prices are known, although these parameters have a certain influence on results. In test cases it was evident that other parameters didn't have a major influence on the final results.

Main driving factors for CO_2 reduction are the improvement of conversion efficiency of fossil technologies, and the increase in the share of CHP and renewables (wind and hydro), but also the reduction of grid losses of heat and electricity and energy conservation and efficiency measures [V].

6.5.1 Total capacity of the wind turbines

As Estonia is a small power system, the size of the installed wind power capacity has important implications for the real-time operation of the system. Here it is assumed that maximum capacity could be technically around 1000 MW. This means that the wind parks will contribute about 50% to the maximum in the year 2020. In the current thesis three sizes of total wind power generators in 2020 are assumed:

- wind turbines with total capacity of 400 MW
- wind turbines with total capacity of 700 MW
- wind turbines with total capacity of 1000 MW

6.5.2 The cost of wind power

The most useful point of reference for investment cost is the latest wind park development cost in Estonia (investment cost of Vanaküla and Tooma wind parks). The wind parks are constructed as a turn-key project. The cost per kilowatt would be in the range 1025-1340EUR/kW. The construction of an offshore wind park would be even more expensive (Table 6-3).

Table 6-3 Average investment and fix costs of the wind park

Investment	MEUR/MW
Onshore wind	1.2
Offshore wind	1.5-2.0
Fixed costs (per year)	
Onshore wind	0.05
Offshore wind	0.09

The analysis has been carried out using the Estonian MARKAL model [V], [47], [63].

6.6 Results of modelling scenarios with Markal

Main driving factors for CO_2 reduction are the improvement of conversion efficiency of fossil technologies, and the increase in the share of CHP and renewables, but also the reduction of grid losses of heat and electricity and energy conservation and efficiency measures.

It should be mentioned here that since the MARKAL model is based on the concept of a Reference Energy System and therefore the representation of energy flows differs slightly from the official energy balance statistics. Also the MARKAL model cannot describe the electricity sector in the required detail, thus additional analysis is needed for balancing issues and the accommodation in the power grid.

Current study did not use the electricity and biomass net import options as possible ways to cover domestic demand and reduced greenhouse gas emissions.

Future decisions concerning oil-shale, natural gas and coal depend completely on the future of the CO_2 price. If the price is high, it is not practical to install a large amount of carbon intensive technologies.

New thermal condensing capacity will be built using CFBC and supercritical CFBC technology during 2015-2030. These will replace more than half of initial installed capacity of the old pulverized combustion plants. Condensing natural gas power plants will be built starting from 2010. Their capacity will be substantial, but their utilization factor will be very low. They will be used for covering sharp peak loads, balancing wind power and for reserve capacity. The security of the Russian gas supply is an extremely important factor here.

Besides oil-shale, Estonia has two main domestic energy sources – the renewables biomass and wind. Hydro resource usage is limited and the total potential is only ca 30 MW.

Total capacity of peat and biomass based CHP plants will increase quite rapidly, thus providing the main future solution for heat production as well. The CHP potential will be used fully at the end of the planning period in all scenarios; only the market shares of different fuels differ by scenario (peat and biomass). Total capacity of peat and biomass based generation will reach 300 MW in 2035.

Wind power increases hand in hand with higher CO_2 prices. The total wind capacity limit will be reached in 2020 with a high CO_2 cost.

The wind scenarios were formed for wind turbines with total capacity of 400, 700 and 1000 MW. All scenarios were analysed with high and low CO2 cost. CO_2 cases, with cost 40 EUR/ton and 75 EUR/ton, were analysed. The main results achieved using the MARKAL model concerning wind turbines are presented in Table 6-4. The objective function of the optimisation was determined to be the minimisation of total emission cost for CO_2.

Table 6-4 shows the total CO_2 costs of the Estonian energy system under different wind scenarios and two CO_2 cost levels. The cost differences between the low wind case and cases with high wind power available vary by a maximum of 2-4 %.

Table 6-4 Total discounted CO_2 cost, 10^9 EEK = GigaEEK (further, GEEK)

INVESTMENT ALTERNATIVES	CO_2 - low	CO_2- high		minimum
wind 400 MW	880 859	1 651 611		880 859
wind 700 MW	863 942	1 619 892		863 942
wind 1000 MW	849 298	1 592 434		849 298

According to the results it could be presumed that with lower CO_2 costs, large-scale wind power integration is not feasible as its main effect is strictly connected with emissions prices and it is not competitive with conventional generation. Both examined CO_2 cost scenarios show that higher wind level guarantees the higher emission reduction.

6.7 Wind power investment decision making under uncertainty

6.7.1 General

In order to evaluate and choose among alternatives, all the possible alternatives and possible outcomes are listed. With MARKAL all possible outcomes for each alternative were calculated (Table 6-5).

Maxmin, LaPlace and Minmax decision modelling techniques are applied to choose an alternative. The results with total discounted CO_2 emission cost are presented.

Table 6-5 Payoff table, GEEK

INVESTMENT ALTERNATIVES	CO_2 - low	CO_2- high
wind 400 MW	0	0
wind 700 MW	16 917	31 719
wind 1000 MW	31 561	59 177

6.7.2 Decision making using total CO_2 cost

An Example of the Maxmin Criterion

For each action, the worst outcome (smallest reward) is determined. The maximin criterion chooses the action with the “best” worst outcome (Table 6-6).
Thus, the maxmin criterion tends towards the adoption of the variant with wind power of 1000MW.

Table 6-6 Payoff, maxmin criterion, GEEK

INVESTMENT ALTERNATIVES	CO_2 - low	CO_2- high
wind 400 MW	0	0
wind 700 MW	16 917	31 719
wind 1000 MW	31 561	59 177

Maxmin criterion
minimum
0,00
16916,95
31560,83

maxmin payoff	31560,83
maxmin decision	wind 1000 MW

An example of the Equally Likely (LaPlace) Criterion

The Equally Likely, also called LaPlace, Criterion finds the decision alternative with the highest average payoff (profits); lowest average payoff (costs). The average payoff for every alternative is calculated in Table 6-7. The optimum is the alternative with the maximum average payoff.

Thus, the LaPlace criterion tends towards the adoption of the variant with wind power with the total amount of 1000 MW.

Table 6-7 Payoff, Equally Likely (LaPlace) Criterion, GEEK

INVESTMENT ALTERNATIVES	CO_2 - low	CO_2 - high
wind 400 MW	0	0
wind 700 MW	16 917	31 719
wind 1000 MW	31 561	59 177

Equally Likely (LaPlace) Criterion
average
0,00
24318,12
45368,69

Equally Likely (LaPlace) Criterion	45368,69
LaPlace decision	wind 1000 MW

An Example of Minmax Regret Criterion

The minmax criterion fits both a pessimistic and a conservative decision maker approach. The payoff table can be based on lost opportunity, or regret. The rows correspond to the possible decision alternatives, the columns correspond to possible future events. To find an optimal decision, for each state of nature the best payoff over all decisions is determined. Regret is calculated for each decision alternative as the difference between its payoff value and this best payoff value.

The regret matrix obtained with the help of the data from Table 6-5 applying the condition $\min_i \max_j (R_{ij})$ to the matrix, is presented in Table 6-8.

Thus, the minmax regret criterion tends towards the adoption of the variant with nuclear power plant 1000 MW.

Table 6-8 Regret, Minmax Regret Criterion, GEEK

INVESTMENT ALTERNATIVES	CO_2 - low	CO_2 - high	maximum
wind 400 MW	31 561	59 177	59177
wind 700 MW	14 644	27 457	27457
wind 1000 MW	0	0	0

minmax regret	0
minmax decision	wind 1000 MW

6.8 Optimal introduction of large-scale wind power under uncertainty

Understandably, the future of wind power depends completely on future CO_2 prices. If the price is low, the wind technology is not competitive without subsidies. The results with total CO_2 cost show that all the criterions (maxmin, LaPlace and minmax regret) tend towards the adoption of the wind power variant with a total capacity of 1000 MW in year 2020 with an possible expansion. Offshore wind power development will have a major part to play here to reach such impact level [II].

The current wind power integration level is limited by the balancing capability of the existing and neighbouring power systems, and is also limited by the transfer capabilities of interconnections. Therefore 1000 MW of wind power integration needs substantial power system development (power reserves and power grid reinforcements) and this all requires enormous investments. The current subsidy level would not make such large-scale scenario possible. Also it could be noted that the price of electricity increases rapidly when the price of CO_2 is high or there are high subsidy rate enforced. As usual, the end consumers are very price sensitive and the regulator has to take this into account while making decisions.

There is also one risk factor concerning the competitiveness of wind power in an open electricity market. As it is noticed from power systems with high wind power concentration, when there are high winds and a large amount of wind power available in the market, market prices are expected to be low and consequently economic profitability will suffer. Therefore, the future competitiveness of wind power can be improved considerably if efficient energy storage technologies are implemented. Several concidrable solutions, such as the pumped storage power plant and different types of battery technologies are already under strong investigation.

7 CONCLUSIONS AND FUTURE WORK

If the ambitious European RES based power generation development targets are to be met, the adaptations of the power system infrastructure are unavoidable to integrate large shares of wind power.

In this work, the impact of large-scale wind power on the Estonian power system was studied.

The first main focus was set on wind power forecasting issues as it is a commonly proven fact that the forecasting of wind power output plays an important role in the shortrun operation of wind power in the power system since the wind power generation is considerably more variable than conventional generation and the capacity value of wind park is limited. The actual wind park short-term forecast performance and the results of preliminary experiments using a neural network to predict wind power generation are presented. The predictions are compared to those of a simple physical model. The results show useful performance of the neural network model, but also clearly indicate that further experimenting is needed before the model can reach its full potential. The future challenge is to use the optimal set of tools and configurations for a specific forecast application. The biggest potential for further improvements will be in the very short-term prediction up to a few hours ahead.

The second part of the work focuses on the accommodation of large-scale wind power into the power system. The technical requirements for wind power and risen grid related issues are given. The possibilities of large-scale wind park integration into the power system and its balancing options are investigated.

Estonia has very good wind resources but unfortunately the power grid in those regions is not so well-developed and access to regulating power is quite limited. Therefore, the key factors for smooth and optimal large-scale wind power integration are the grid structure upgrade and the security of the sufficient amount of balancing units in the power system.

When connecting wind parks at various locations across the country, the transmission reinforcement cost needs to be considered. Wind power integration should be assessed at the international level, to identify the needs and benefits of interconnection of national power systems. For high penetration levels of wind power, the optimization of the integrated system should be explored. Modifications to system configuration and operation practices to accommodate high wind penetration may be required.

Do ensure the power balance and secure power of supply, an adequate amount of fast-starting generating units must be available. In the system without major hydro potential, the gas turbine would be most common option. The additional requirements and costs of balancing the system on the operational time scale are primarily due to the fluctuations in power output generated from wind.

Nevertheless, the long lead times of transmission grid reinforcements and adequate regulating power units' availability remain critical obstacles for wind turbines, even if grid reinforcement's costs and regulating power plant investments are covered by consumers.

In the third part of the work, the main methods for optimizing the unit commitment schedules are described. The short-term generation scheduling model for balancing fluctuating power output of large wind parks is introduced, which can be used also in other power systems. In the calculations the Lagrange relaxation method is used and first results to be used within Estonian power system are analysed. Provided results underline the importance of intermediate energy storage existence in the system. It is especially crucial in the power systems, where the base load is covered with only the thermal power plants. The improved energy storage systems would be most efficient in cases where urgent and larger variations between scheduled and actual wind power generation occur.

How useful the wind power will finally be to a power system depends on the ability of other units in the system to meet the wind power variations. As capacious wind power is introduced to a power system the capacity factor of the other units in the system will decrease. The extent of the decrease depends on the ability of the unit to adjust its generation pattern to the wind power production, relative the ability of other units in the system to adjust their generation and, to some extent, to export capacities to some region outside that of the system in dispatch.

The aim of the final part of the work is to present a shortened long-term generation expansion planning approach for environments with an uncertain future. The approach is tested on the Estonian case for introduction of large-scale wind power. This methodology can be used for evaluating different types of technologies and it can be also used in other power systems. The most important aim was the reduction of CO_2 emissions. According to the result it could be pointed out that with lower CO_2 costs, large-scale wind power integration tends to be not feasible as it main effect is strictly connected with emissions prices and it is not competitive without subsidies. The higher CO_2 costs leads to the implementation of wind power in the Estonian power system with total capacity of 1000 MW by the year 2020 and it could be achieved through offshore wind power development. For balancing purposes the gas turbines, fired by natural gas and/or light fuel oil, and pumped storage power plant are used. The actual decisions towards implementation of large-scale wind power in the future will be affected by the investment decisions, social costs and political influences that are not considered in the power system optimization process.

There are several other important factors of successful wind power integration what are not analysed in the current work since these assumptions can change overnight. The main factor here is an adequate support system for electricity produced from wind which has been main motivator and real pusher for many countries. Usually the larger subsidies mean the higher attraction in wind power development which makes the large-scale wind power expansion possible. Also, capacious wind power integration is usually directly connected with offshore development and it depends on existing legal framework (general planning for offshore areas, seabed usage rights, procedures of building permit, etc.).

The current work and the previously discussed subjects do not end here. There are several further areas to be studied to make the larger wind energy expansion possible. One of the key factors would be considerable improvements in the wind power forecast systems development which could introduce competitive wind power to the power system-markets.

Similarly important area is to develop further methods for optimal power balancing systems and to introduce more technically optimal storage solutions into the power sector. Distributed wind generation solutions among the smart grid settlements will hold the key position for the future trends.

The research in wind generation planning under uncertainty will also need to be improved. The present research concentrates only on the most important uncertainties relating to the introduction of wind power in Estonia. Further work must therefore include all uncertain factors that may affect future decisions and more precise models should be used which could improve the precise modelling of system load and the future electricity market area. Futher development of fuzzy logic should be an effective approach for tackling problems related to uncertain future. Therefore fuzzy system applications for long-term generation planning should be considered.

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PUBLICATIONS RELATED TO THE TOPIC

I. **Agabus, H.,** Tammoja, H. Wind Power Production Estimation Through Short-Term Forecast. Oil Shale, Vol. 26, No. 3 Special, pp. 208-219. 2009 Estonian Academy Publishers ISSN 0208-189X.

II. **Agabus, H.,** Palu, I., Tammoja, H. Hiiumaa large-scale offshore wind park integration into Estonian grid. 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. Madrid, Spain 2008: Energynautics GmbH. pp. 498-501.

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VIII. Landsberg, M., **Agabus, H.,** Liik, O. CO_2 emission reduction options for Estonia. 3rd International. Symposium “Topical Problems of Education in the Field of Electrical and Power Engineering”. Doctoral School of Energy and Geotechnology: Kuressaare, Estonia, January 16-21, 2006. Tallinn: Tallinn University of Technology, Department of Electrical Drives and Power Electronics. 2006. pp. 112-119. ISBN 9985-69-036-2.

IX. **Agabus, H.,** Landsberg M., Liik, O. Optimal Investment Strategies for Energy Sector Under Uncertainty. 2nd International Symposium “Topical Problems of Education in the Field of Electrical and Power Engineering”. Doctoral School of Energy and Geotechnology: Kuressaare, Estonia, January 16-21, 2006. Tallinn: Tallinn University of Technology, Department of

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XI. Palu, I., **Agabus, H.** Wind energy integration impact on power quality in Estonia. In Proc: European Wind Energy Conference, 8-10 May, 2007, Milan, Italy: EWEC, 2007. (CD-ROM). pp. 1–6.

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XIII. Tammoja H., Palu, I., **Agabus, H.,** Keel, M., Oidram, R. An optimal model for balancing fluctuating power of large wind parks. 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. 14-15 October, 2009, Bremen, Germany 2009: Energynautics GmbH (accepted).

XIV. Kilter, J., Tsernobrovkin, O., Landsberg, M., **Agabus, H.,** Palu, I. Possibilities and analysis of integration of large-scale offshore wind parks into Estonian power system. 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms. 14-15 October, 2009, Bremen, Germany 2009: Energynautics GmbH (accepted).

XV. **Agabus, H.,** Palu, I., Le, T. A.., Warland L., Uhlen, K. Nordic power system options for balancing Estonian large-scale wind energy. Power system Integration and Electrical Systems of Wind Turbines and Wind Farms. Nordic wind power conference, 10-11 September, 2009, Bornholm, Denmark. (accepted).

ABSTRACT

Large-Scale Integration of Wind Energy into the Power System Considering the Uncertainty Information

The introduction of wind power on a large-scale affects the entire power system. The inflexibility, variability, and relative unpredictability of intermittent power sources are the most obvious barriers to an easy integration and widespread application of wind power.

The purpose of the thesis is to investigate the impact of large-scale wind power on the power system operation and Estonian power system is used here as the reference case. The thesis presents the main technical-economical challenges what includes short-term wind power forecast, transmission grid planning, securement of adequate balancing reserves and system generation scheduling in order to minimize the total fuel cost. In addition, the thesis introduces an efficient energy system development strategy in electric utility long-term planning under conditions of uncertainty. Here, the main focus is on the introduction of large-scale wind power in the Estonian power system under conditions of uncertainty relating to the long-term CO_2 price.

As the amount of wind power production grows in proportion to the electric load and other resources in the generation portfolio, errors in wind generation forecasting become very significant to system operations. Current thesis presents single wind park short-term forecast results of preliminary experiments using a neural network to predict wind power generation. The predictions are compared to those of a simple physical model.

Estonia has very good wind resources, but unfortunately the power grid in those regions is not so well developed what makes substantial wind power integration very difficult. According to the investigated offshore wind park case, the key factors for smooth and optimal large-scale wind power integration are the grid reinforcements and the security of the sufficient amount of balancing units in the power system. All of this will require substantial level of long-term investments.

The model run made with the short-term generation scheduling model indicates that problems related to the unit commitment and the optimal load dispatch could be solved, when mathematical optimization methods are used, what will secure the minimum fuel cost for the entire power system.

Long-term generation expansion planning approach for environments with an uncertain future presents a large-scale wind power outlook for the future. The most important aim here is the reduction of CO_2 emissions. The energy system of Estonia is modelled with MARKAL. MARKAL is a dynamic linear programming model of the technical energy system, used to explore different energy-environmental policy scenarios. As an outcome, an optimal scenario for the introduction of large–scale wind power under uncertainty is developed. According to the results, the future of wind power depends completely on future CO_2 price and is not probably competitive without adequate subsidies.

KOKKUVÕTE

Elektrituulikute integreerimine energiasüsteemi arvestades informatsiooni mittetäielikkust

Mahukas tuuleenergia integreerimine energiasüsteemi mõjutab kogu süsteemi edasist talitlust. Tuuleenergia vähene paindlikus, ebastabiilsus ning relatiivne prognoosimatus on silmnähtavaks barjääriks hõlpsa ja laialdase tuuleenergia kasutamiseks.

Käesoleva töö eesmärk on uurida ulatusliku tuuleenergia kasutamise mõju elektrisüsteemi talitlusele Eesti energiasüsteemi näitel. Töö esitleb tuuleenergia põhilisi tehnilis-majanduslike väljakutseid, sealhulgas lühiajalist tuuleenergia toodangu prognoosi, ülekandevõrgu planeerimist, piisava reservvõimsuste tagamist ja kütuse kogukulu minimeerivat genereerimisvõimsuste koormusjaotust. Täiendavalt tutvustatakse tõhusat arengustrateegia meetodit energiasüsteemi arengu planeerimiseks määramatuse tingimuses. Tähelepanu on siin peamiselt suunatud CO_2 kulude pikaajalisest prognoosimatusest tingitud määramatusele ja suurte tuulevõimsuste võimalikule arendamisele neis tingimustes.

Tuuleenergia tootmisvõimsuste suurenemisega kaasnevad toodanguprognoosi vead mõjutavad aina enam kogu süsteemi talitlust. Käesolev töö esitab näitena kasutatud tuulepargi lühiajalise toodanguprognoosi tulemused. Omavahel võrreldakse närvivõrgustikuga prognoosisüsteemi ja lihtsa füüsilise mudeli kasutamisel saadud tulemusi.

Eestis on palju heade tuuleomadustega piirkondi, milles paraku ei ole suuremahuliste tuuleenergia tootmisvõimsuste integreerimiseks piisavalt tugevat elektrivõrku. Töös uuritud avamere tuulepargi näite kohaselt on suuremahulise tuuleenergia integreerimise eeldused elektrivõrgu ulatuslik tugevdamine ja süsteemis piisava tasakaalustusvõimsuste tagamine. Mõlemad tegevused nõuavad suuri investeeringuid.

Genereerimisvõimsuste lühiajalise planeerimismudeli tulemused näitavad, et agregaatide valikust ja optimaalsest koormusjaotusest tulenevaid probleeme saab edukalt lahendada matemaatiliste optimeerimismeetodite abil. Need tagavad süsteemis kui tervikus minimaalse kütusekulu.

Genereerimisvõimsuste kasvu pikaajaline planeerimine määramatuse tingimuses tõstab esile mahuka tuulevõimsuste tulevikuperspektiivi, mille juures on peamine eesmärk CO_2 heite vähendamine. Töö käigus modelleeriti Eesti energiasüsteem MARKALi mudeli abil, mis on tehnilise energiasüsteemi dünaamiline mudel ja kasutab erinevate energia- ja keskkonnastsenaariumite modelleerimiseks lineaarset optimeerimist. Töö tulemusel töötati välja universaalne lahend tuuleenergia ulatuslikuks kasutuselevõtuks Eesti energiasüsteemis. Vastavalt uuringu tulemustele sõltub tuuleenergia tulevik Eestis täielikult CO_2 edasistest hinnamuutustest ja on tõenäoliselt konkurentsivõimeline vaid toetusskeemide toel.

ELULOOKIRJELDUS

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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2004	elektroenergeetika eriala, tehnikateaduste magister
Tallinna Tehnikaülikool	2002	elektroenergeetika eriala, tehnikateaduste bakalaureus
Tallinna Laagna Gümnaasium	1998	keskharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
eesti	emakeel
inglise	kõrgtase
saksa	algtase
vene	algtase
soome	algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2002-2006	Fingrid Oy, Soome
2003,2005	HRM
2003-2005	EMI EWT

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2007-jätkub	OÜ Nelja Energia	Arendusjuht
2001-2007	OÜ Põhivõrk (Elering)	Võrguanalüütik

7. Teadustegevus

- Eesti Teadusfondi grant G4276 "Võimalused elektituulikute kasutamiseks Eestis", välisekspert
- EL Phare CBC 2003 projekt "Tuuleenergia rakendamine ja integreerimine energiasüsteemiga Balti mere regioonis", välisekspert
- Nordic Energy Research (NER) project „ Elektrisüsteemi analüüsmudeli arendus", täitja

8. Kaitstud lõputööd

- Magistritöö: "Baltimaade ülekandevõrkude arengustsenaariumid", 2004, juhendaja prof. Olev Liik
- Bakalaureusetöö: "Põhivõrgu arengu mõju reaktiivvõimsuse bilansile Eesti elektrisüsteemis", 2002, juhendaja dots. Eeli Tiigimägi

9. Teadustöö põhisuunad

Elektrituulikute ja energiasüsteemi koostöö modelleerimine, toodangu prognoosimine, optimaalse võrgustruktuuri valik ja tuulikute balanseerimisvõimaluste analüüs. Elektritootmise optimaalne struktuur ja paigutus, erinevate elektritootmisviiside analüüs lähtuvalt tulevikustsenaariumidest, erinevate elektritootmisviiside mõju hindamine keskkonnale

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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn Technical University	2004	electrical power engineering master of technical sciences
Tallinn Technical University	2002	electrical power engineering, bachelor of science
Tallinna Laagna Gümnaasium	1998	secondary education

4. Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	mother tongue
English	fluent
German	basic skills
Russian	basic skills
Finnish	basic skills

5. Special Courses

Period	Educational or other organisation
2002-2006	Fingrid Oy, Finland
2003,2005	HRM
2003-2005	EMI EWT

6. Professional Employment

Period	Organisation	Position
2007-present	OÜ Nelja Energia	Development manager
2001-2007	OÜ Põhivõrk (Elering)	Grid analyst

7. Scientific work
   - Estonian Science Foundation grant project G4276 “Possibilities and efficiency of the use of wind generators in Estonia”, external expert
   - Phare CBC 2003 project “Introduction and integration of wind power in the Baltic Sea Region”, external expert
   - Nordic Energy Research (NER) project “Model Development for Power System Analysis”, executor

8. Defended theses
   - Master thesis: “Baltic transmission grids development scenarios”, 2004, supervisor prof. Olev Liik
   - Bachelor thesis: “Estonian national grid development influence for reactive power balance in Estonian power system”, 2002, supervisor assos. Prof. Eeli Tiigimägi

9. Main areas of scientific work/Current research topics
   - Modelling of wind turbine generators cooperation with power system, wind power forecast, analysis of optimal grid structure and selection of optimal balancing structure. Optimal structure and allocation of power generation, elaboration of different power conversion technologies for the future, impact of different energy conversion technologies on the environment

APPENDIX A

Paper I

Agabus, H., Tammoja, H. Wind Power Production Estimation Through Short-Term Forecast. Oil Shale, Vol. 26, No. 3 Special, pp. 208-219. 2009 Estonian Academy Publishers ISSN 0208-189X.

Paper II

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