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CO-OPERATION OF ESTONIA'S OIL SHALE BASED POWER SYSTEM WITH WIND TURBINES

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During the negotiations with EU, Estonia was set an indicative target to increase the share of renewable energy sources in the electricity production to 5.1% by the year 2010. One of the main means to achieve this target is to install wind generators. This paper analyzes the capability of the existing power system to integrate large amounts of wind power and shows that involvement of large-scale oil shale power plants in the compensation of fluctuating production of wind turbines eliminates a substantial part of the expected positive effect of wind energy.

Introduction

Increasing the share of renewable energy in the production of electricity is an important issue everywhere in the world. The use of wind energy is one of the most attractive options here, especially in the countries with long coastline and many islands like Estonia. In spite of remarkable wind potential similar to Denmark, only 6.2 MW of wind potential was utilized in Estonia at the end of the year 2004.

The wind energy projects were unfeasible during a long period due to the low price of electricity in the existing power system and Estonia's very limited possibilities to subsidize wind-generated electricity. In addition to that, multiple technical constraints existed as well. During the last ten years electricity tariffs have raised several times and they continue to increase, the purchasing obligation and feed-in tariffs for electricity from RES have been written into legislation, and construction of wind generators has improved substantially. This has recently caused a new peak of interest in wind energy investments and even in local manufacturing of wind turbines to reduce the price of equipment.

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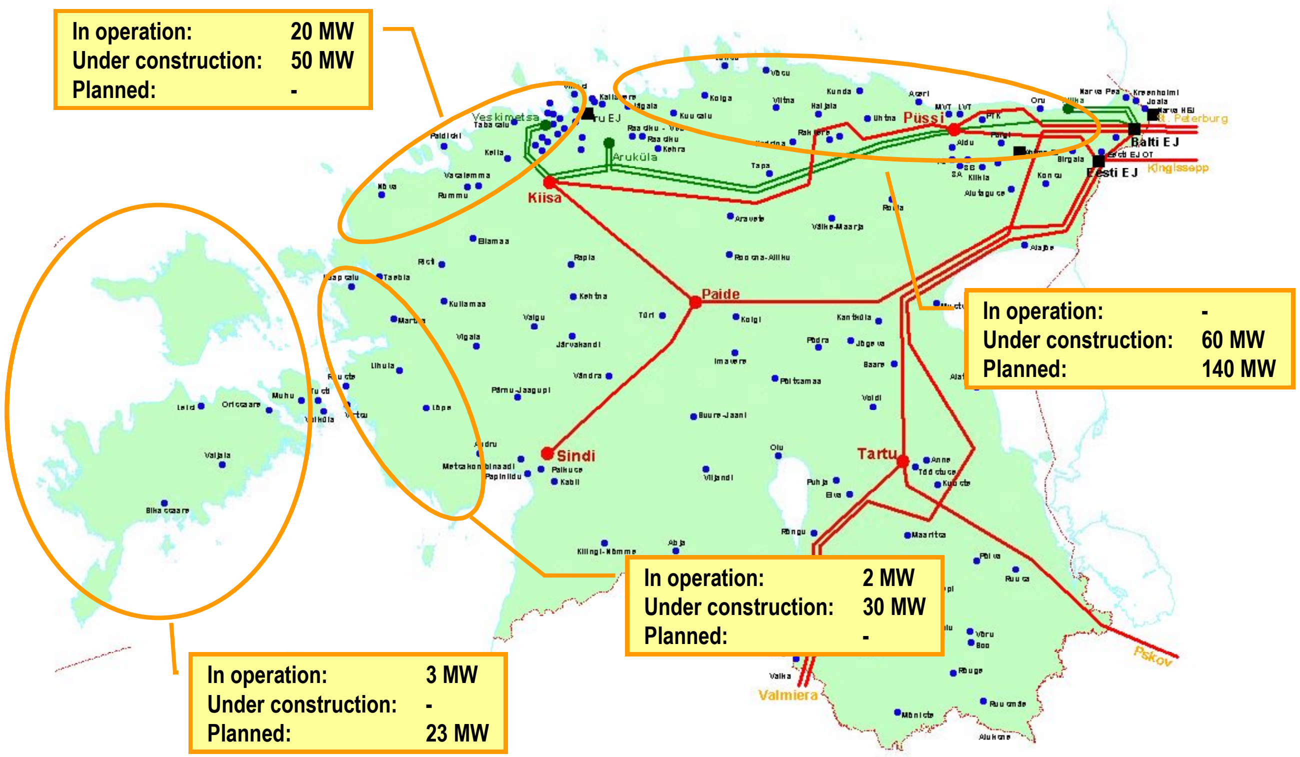

Fig 1. Expected situation in wind power generation in Estonia as of the first quarter of 2005

This interest is supported also by national target to increase the share of renewable energy in the electricity production up to 5.1% from the gross inland consumption in 2010.

This target was set to Estonia by European Union during the accession negotiations. In 2001 the share of renewable energy was only 0.1%. Estonia has three possibilities to reach this hard and expensive target: to develop biomass and wind power plants and to restore small hydro plants. As the total hydro potential is only ca 30 MW, biomass and wind have to fulfil the major part of the goal.

This situation in wind energy use is going to change rapidly in the near future. New "wind boom" during the last years has resulted in grid connection applications for more than 600 MW (*ca* one third of the total net capacity of existing power plants). Construction of a 20-MW wind farm was finished in January 2005, and several other wind projects will start the construction phase in 2005. The expected situation of wind power production in Estonia as of the first quarter of 2005 is depicted in Fig. 1. An extremely fast growth of the use of wind potential raises the following questions: how many wind turbines can the present system integrate, what will be the costs of this expansion and what benefits can be achieved?

The aim of this paper is to analyze the capability of Estonian power system to integrate large amounts of wind capacity and to evaluate the necessary technical measures and investments into the existing system. The aim is also to show that the fuel economy and reduction of emissions in the power system that consists mainly of fossil-fuel power plants is not proportional to the electricity production of wind turbines. Involvement of thermal power plants in the compensation of fluctuating production of windmills will reduce the expected positive effect of wind energy. The latter is a phenomenon specific not only of Estonia. A similar situation appears also in power systems involving hydroelectric power plants, as the hydroplants cannot fully compensate the fluctuations of wind power.

The methods for calculating the environmental gain from wind power that are used in the feasibility studies of wind farms, climate change studies, long-term energy system planning and in other similar purposes, are usually linear and very simple. Such simplicity may cause serious overestimation of the achievable positive effect of wind power.

The accounting of emission reductions is also linear in the MARKAL model [1] that has been used by TUT in the long term planning of Estonia's energy sector and climate change studies since 1994 [2], [3]. MARKAL optimizes the fuel mix and set of technologies, but it cannot consider additional emissions due to the compensation of fluctuations in wind power with the power from fossil-fuel power plants.

The basic concept of the methodology for calculating the real environmental gain from wind power was first published in Estonian in [4] and developed further under the grant project of Estonian Science Foundation [5]. The most comprehensive presentation of this methodology can be found in [6].

Problem of Balancing of Fluctuations in Wind Power

It is well known that wind power plants are almost uncontrollable, their power varies rapidly and frequently within a wide range, as their output power is a function of the wind speed in the third power, their production is hard to forecast, and they cause various technical problems and require additional investments in the system.

A power curve of wind turbines of Western Denmark during one month (May 2002) that bases on the statistical data from [7] is depicted in Fig. 2, and it will serve as an example of the wind energy production in this paper.

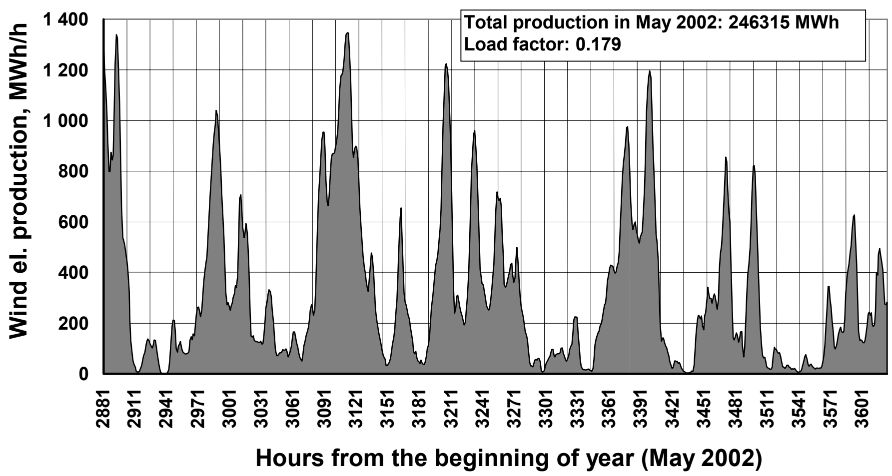

Fig. 2. Production of wind-generated electricity in Western Denmark in May 2002

For the reasons listed above, the integration of windmills into the existing power system is not easy. It depends on the size and structure of a concrete power system and on the capacity of links with neighbouring systems. Systems that contain considerable amount of hydropower are in a favoured situation. Hydropower is controllable, fast and renewable. Until all the fluctuations of wind power can be compensated with hydroelectric power plants, the integration of windmills does not trouble the existing system too much, and the environmental gain is linearly proportional to the produced amount of electricity.

The situation is different in the power systems like the Estonian and Danish ones that include only thermal power plants, or in case the installed capacity of windmills exceeds the regulation capacity of hydro plants. As the CHP plants usually follow the thermal load, the condensing power plants must participate in the compensation of wind power fluctuations. Large condensing units cannot be switched on and off frequently and for a short period, and their speed of increasing and decreasing of power is limited. Gas turbines suit best for regulation of the load being of high capacity of fast reserve. If someone wants to introduce large amount of wind power, the power regulating range and speed of the existing plants must be also extensive.

Fast development of utilization of wind energy in several countries has brought them to the situation where the balancing of wind power is not easy any more. Publications like [8] show that the problems connected with expansion of wind energy, having been discussed only theoretically in Estonia for a long time, have become important in the countries which have developed the wind power rapidly in practice.

Operating a thermal plant with and without the need to compensate the fluctuations in wind power is similar to running a car in the city and on the highway, respectively. Fuel consumption of a car can be even double in the city comparing with the highway due to constant accelerating, braking and idle run in the traffic lights.

Calculation of Environmental Effect of Wind Power

In order to calculate emissions from the power system, we proceed from the problem of optimal load planning.

The objective of optimal load scheduling in a power system with thermal power plants and wind generators is the minimization of the total fuel cost (can be also fuel consumption or emissions) at a certain time interval.

To simplify the formulas, let us consider the power system that consists only of thermal plants and wind generators (e.g. Denmark today or Estonia in the future). The similar situation appears also in the other power systems if the hydro plants cannot compensate the fluctuations of wind power.

The optimization model with discrete time can be stated as

$$\min_{P_T} \sum_{k \in K} \sum_{i \in I} C_{ik}(P_{Tik}) \cdot \Delta t_k \tag{1}$$

subject to the following constraints:

- power balance equations

$$P_{D\Sigma k} + P_{Lk}(P_{Tk}, P_{Wk}, P_{Dk}) - \sum_{i \in I} P_{Tik} - P_{W\Sigma k} = 0 \, ; \quad k \in K \tag{2}$$

- power limitations of thermal plants

$$P_{Tik}^{-} \le P_{Tik} \le P_{Tik}^{+} \;, \quad i \in I \,, \quad k \in K \tag{3}$$

- limitations of total power of wind generators

$$0 \le P_{W\Sigma k} \le P_{W\Sigma k}^{+} \,, \quad k \in K \tag{4}$$

- and spinning reserve constraints

$$\sum_{i \in I} P_{Tik}^{-} + P_{W\Sigma k}^{+} - P_{W\Sigma k} \le \sum_{i \in I} P_{Tik} \le \sum_{i \in I} P_{Tik}^{+} - P_{Rk} - P_{W\Sigma k} \,, \quad k \in K \tag{5}$$

where i – thermal plant index, $i \in I = \{1,...,n\}$;

k – time subinterval index, $k \in K = \{1,...,s\}$;

P_{Tik} – active power, generated at i^{th} thermal plant in k^{th} subinterval;

C_{ik} – fuel cost of i^{th} thermal plant in k^{th} subinterval;

Δt_k – duration of k^{th} time subinterval;

$P_{D\Sigma k}$ – total active power demand of power system in k^{th} subinterval;

P_{Lk} – total transmission losses in k^{th} subinterval;

P_{Tk} – vector of active powers of thermal plants in k^{th} subinterval;

P_{Wk} – vector of active powers of wind generators in k^{th} subinterval;

$P_{W\Sigma k}$ – total wind power generation in k^{th} subinterval;

P_{Dk} – vector of power system loads in k^{th} subinterval;

P_{Rk} – spinning reserve requirement in k^{th} subinterval;

x^-, x^+ – lower and upper limits of x, respectively.

The problem (1)–(5) gives an opportunity to determine optimal active power generation schedules of thermal plants in the ideal case, when all the initial information is known exactly and optimal power schedules will be implemented exactly.

In the simplest case optimal powers of thermal plants are determined by equations

$$\frac{b_{1k}}{1-\sigma_{1k}} = \frac{b_{2k}}{1-\sigma_{2k}} = \cdots = \mu_k \tag{6}$$

$$P_{D\Sigma k} + P_{Lk} - \sum_{i \in I} P_{Tik} - P_{W\Sigma k} = 0 \tag{7}$$

and inequalities (3), where

$b_{ik}(P_{Tik}) = \dfrac{\partial C_{ik}(P_{Tik})}{\partial P_{Tik}}$ is the incremental cost characteristic of i^{th} thermal power plant,

$\sigma_{ik} = \dfrac{\partial P_{Lk}}{\partial P_{Tik}}$ is the incremental cost of total transmission losses for i^{th} power plant and

μ_k is the Lagrange multiplier in k^{th} subinterval.

The fuel costs and consumptions and emissions can be read from the corresponding characteristics of thermal plants using calculated optimal powers. Reduction of emissions from a power system due to wind energy use is calculated as the difference of emissions between optimization results with and without wind power.

In real life, the optimization process has to be implemented under incomplete information. The main uncertainty factors in the model (1)–(5) are:

a) the total active power demand of power system $P_{D\Sigma k}$;
b) the active powers of wind generators P_{Wk} and total wind power generation $P_{W\Sigma k}$;
c) the dynamic input-output characteristics of thermal plants $C_{Tik}(P_{Tik}, Z_{Tik}, k)$ and $Z_{Tik+1}(P_{Tik}, Z_{Tik}, k)$, where Z_{Tik} is vector of state variables;
d) the random deviations of actual values of power plant generations from the planned values.

The minmax setup and solution of the problem of optimal load scheduling in the hydro-thermal power system under uncertain information are described in [9]. In this task, the characteristics of thermal plants can be considered static ones.

If we deal with the necessity of compensating wind power fluctuations with the power produced at thermal power plants, the fuel cost characteristics must be considered dynamic ones. Under dynamic characteristics the fuel cost in the time interval *k + 1* depends on the power in the interval *k*, power in the interval *k + 1*, and speed and direction of the change of power.

The use of dynamic characteristics makes the optimization task highly complicated. The mathematic meaning of dynamic optimization lies in the solution of differential equations.

Usually the dynamic fuel consumption characteristics are not known. Their determination requires expensive experiments, and sometimes the dynamic characteristics cannot be determined at all, due to the absence of necessary exact measurement equipment (for example in the case of Estonian oil-shale power plants).

Considering the absence of dynamic input-output characteristics of thermal power stations, the uncertain nature of a large part of key input data and a need to simplify the calculation method, an easy two-step approach can be used [6]:

1. calculation of additional fuel consumption (cost, emissions) for keeping maximum amount of spinning reserve and determining of corresponding new point of fuel consumption characteristic,
2. parallel shift up of the initial characteristics to the new position, and use of the new characteristic as rough substitute of the dynamic fuel consumption curve.

This approach is highly simplified, but it enables the use of existing planning software with minor modifications. It gives an opportunity to get more realistic results than the linear methods of calculation of emissions reduction.

Co-Operation of Oil Shale Power Plants with Large-Scale Wind Farms

To examine the impact of large-scale introduction of wind power on the fuel consumption and emissions of Estonian oil shale power plants, the methodology proposed in [5, 6] was used, and a fictional power system was composed on the basis of data from oil shale power plants and wind power production of Western Denmark.

The initial situation and calculation results are presented in Fig. 3.

The initial fuel consumption curve corresponds to the sum of Estonian oil shale power plants, and the wind power fluctuations represent the situation in Western Denmark in May 2002 reduced in scale.

Figure 3 depicts the following curves:

a) normal (static) fuel consumption (or cost or emissions) characteristic of an equivalent oil shale plant, that can be used in planning the operation without wind power (line 1);
b) static dependency of fuel consumption on additional reserve capacity requirement (line 3);
c) dynamic fuel consumption (emissions) characteristic of an equivalent oil shale plant (loop curve);
d) new equivalent static fuel consumption (emissions) characteristic that takes into account additional fuel consumption (emissions) due to keeping additional spinning reserve and compensation of wind power fluctuations (line 2).

Wind power is characterized by the maximum total power (sum of installed capacities of all wind turbines multiplied by the coincidence factor) and the mean power (total installed capacity multiplied by capacity factor). Capacity factor of wind turbines is calculated as the division of wind generated electricity during the considered time period by the total installed capacity of turbines.

In case the wind turbines were ordinary controllable power plants that do not fluctuate and do not need keeping of extra spinning reserve capacity, the normal static fuel consumption characteristics of thermal plants could be used in optimal load scheduling and a 30.7% reduction in fuel consumption (emissions) could be achieved under the maximum power of wind turbines. This is the logic of linear approach to the emissions calculation.

In reality, only keeping the necessary additional reserve capacity will increase the fuel consumption (emissions) by up to 8.1%. To get a more realistic estimate of fuel consumption (emissions) that considers also fluctuations in wind power reduced to the mean power of wind turbines, the initial fuel consumption curve should be lifted up also by 8.1%.

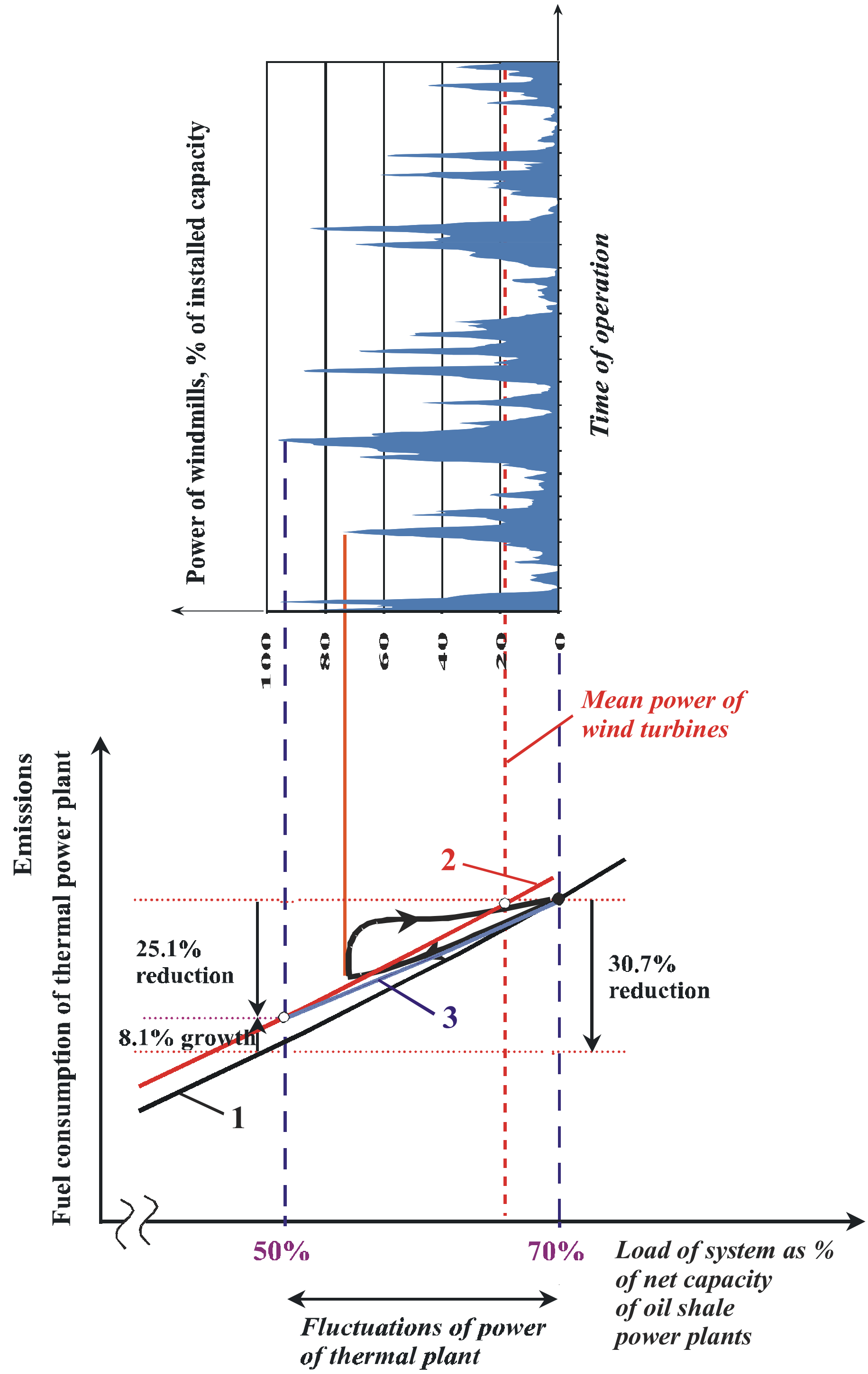

Fig. 3. Results of the calculation of fuel consumption increase on the basis of Estonian power system and Danish wind energy data

The calculations were repeated for several values of power system load, and the results showed at least 8–10% increase in fuel consumption and emissions compared to the steady operation of thermal stations under constant-rated power of wind turbines. In some cases the environmental gain from the wind energy use was almost totally lost.

Possibilities of Integrating Wind Farms into the Estonian Power System

Estonian small power system is one of the world's worst systems for wind power integration. Today its available net capacity is ca 2,300 MW including two largest oil shale power plants in the world, one large CHP firing natural gas, some smaller CHPs and 3.5 MW of hydro- and 6.2 MW of wind power. The annual net inland electricity consumption is 6 TWh (excluding losses), and exports to Latvia and Russia are 1–2 TWh. Annual net electricity consumption *per capita* is ca 4,300 kWh.

Domestic peak load in wintertime reaches 1,500 MW, and low load in summer decreases to 400 MW. The total length of 110–330 kV transmission lines is 5,200 km. Interconnections to the neighbouring systems have total capacity of about 2,000 MW. Estonia has interconnection with Russia *via* three 330 kV lines and to Latvia *via* two 330 kV lines. Electric grids in the coastline and islands are weak. Large oil shale power plants are old (except two reconstructed units commissioned in 2004) and slow, and they are not envisaged for provision of regulating power. Net capacities of units of oil shale plants vary in the range of 160–195 MW.

Technical conditions for connecting wind farms to the electric grid are elaborated by the transmission system operator National Grid, and they are set by the Estonian Grid Code (in force since the 1st of July, 2003). Possible concentration of wind power in a geographically limited area has a severe impact on the power system. The marginal constraints applied until 2003 are gradually replaced by more rigorous requirements for power control, frequency, voltage (including reactive power compensation) and stability during faults in the transmission system in the Grid Code.

According to the Grid Code, a wind farm with installed capacity over 200 kW must be able to 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. The requirements can be summarised as follows:

- During the periods with reduced transmission capacity in the grid (e.g. due to service on lines and/or components of the transmission grid), the wind farm must be able to operate at reduced power levels with all turbines running.
- The production measured as a 1-minute average value must not exceed the power setpoint or the rated power (whichever applies) of the wind farm with more than 5% of the rated power of the wind farm.

- The wind farm must be able, if necessary, to participate in the area balance control (secondary control). In this mode the power setpoint will be determined by the transmission system control and sent to the wind farm through the SCADA-system (Supervisory Control and Data Acquisition system) on a regular basis. The updating interval to the wind turbines will be in the order of 1 second.
- Large and fast variations in the power production can be caused by passing weather fronts and thunderstorms. While there are no countermeasures against sudden drops in the wind speed, the wind farm must be able to impose a positive rate of change of power dP/dt limitation in such situations. The rate setpoint can be set through the SCADA-system to the wind farm main controller which will update the power setpoint to the turbines approximately once a second.
- Large and fast frequency deviations may occur if smaller areas are isolated from the grid, and the wind farms must be able to participate in frequency control in such situations. This control mode should be implemented directly in the wind turbines with adjustable droop, deadband and offset for both control directions. The required control speed is high. The maximum power rate of change should correspond to a reduction in production from 100% of rated power to below 20% in 5 seconds under the worst operating conditions.

The integration of wind power into thermal power system brings the following actual impacts:

1) If the power of windmills remains below the sensitivity of load regulation of large thermal plants (10 MW in Estonian case), no load changes of thermal plants or reduction of fuel consumption or emissions can happen. The fluctuations in wind power are absorbed by the power system inertia, and they can cause only local electricity quality problems. From the other hand, produced wind electricity just "disappears" in the wheeling power of the large interconnected power system. To mitigate this situation, the windmills should have small compensating thermal plants (e.g. natural gas CHP with heat accumulator) nearby. The last option is almost impossible in Estonia owing to low number of population in the windy regions.
2) If the wind power is higher than the system sensitivity limit and does not exceed the limits determined by the summer low load and reserve requirements (10–40 MW in the case of Estonia), the thermal plants have to start compensating the fluctuations in wind power. It is possible to ensure needed yearlong additional reserves up to that bound. Fuel consumption of the system will decrease, but not proportionally to the wind produced electricity.

Limits and Costs of the Integration of Wind Turbines into the Estonian Power System

WTG installed, MW (comments are given below)	Investment into WTG, M€	Investment to the grid, M€	Other costs	Capacity factor, %	Annual production, GWh	Annual subsidies, M€	Share from demand in 2010, %
up to 10[*1]	10	1.5 – WTG connection fees		28	25	0.5–0.7	up to 0.4
40–50[*2]	50	12 – WTG connection fees	In case of gas turbines (GT) costs for compensating wind power fluctuations *ca* 2 M€/y	28	123	2.3–3.1	1.7–2.0
250[*3]	250	25 – WTG connection fees	GT's costs for compensating WTG fluctuations *ca* 7.5 M€/y; investment for GT – 60 M€; reconstruction of secondary regulators in existing power stations *ca* 7.5–9.4 M€	25	550	10.3–13.8	7.6–9.1
Up to 400[*4]	400	35 – WTG connection fees. 50 – for grid reinforcements	GT's costs for compensating wind fluctuations *ca* 12.5 M€, investment into GT – 125 M€; reconstruction of secondary regulators in existing power stations *ca* 9–11.3 M€	24	840	15.8–21	up to 14.0
Over 400[*5]	Over 400	Over 35 for WTG connection fees; over 160 for grid reinforcements	Same as previous + over 19 M€ for buying of reserves annually				

Comments:

[*1] Wind power fluctuations will mostly disappear in total consumption and wheeling power with Russia and Latvia. Installed capacities and fuel consumption of thermal power stations do not change; no positive environmental effect.

Bound is dependent on Estonian low-load demand. Theoretically it is possible to ensure needed year-long reserves up to that bound. It is likely that there is no need to limit active power of WTG-s during operation. If power fluctuations will be compensated by thermal power stations, savings in fuel are minimal, no remarkable positive environmental effect.

[*2] Reserves for compensating wind power fluctuations are theoretically available only during high-load period in wintertime. Rapid fluctuations cannot be compensated by thermal power stations. Problems with system power balance will appear. During WTG-s operation remarkable power limits, especially during low-load period, will exist. Consequently WTG-s utilisation time is lower than it would be in normal conditions.

[*3] About 120 MW of gas turbines is needed to compensate wind power hourly fluctuations. For compensating rapid fluctuations secondary regulators of thermal power stations are to be reconstructed in 6 units.

[*4] Possible only in co-operation with neighbouring power systems. Large reinforcements in grid are needed. 250 MW of GT-s are necessary to compensate power fluctuations. Secondary reserves of existing thermal power stations are not sufficient to compensate rapid fluctuations. During low-load and flood period of Latvian hydro plants, the limitations of active power of WTG-s up to 200 MW are needed.

[*5] Extending investments into the grid are needed. WTG capacity over that level is possible only if new power stations to western and northern part of Estonia will be built (they are needed to increase short-circuit capacity in those parts of Estonia). Also, static var compensators are needed to keep power quality at acceptable level. Reserves in the current interconnected power system are insufficient; new DC links to NORDEL system are needed.

3) With the further increase in wind power (50–250 MW in the case of Estonia), a whole complex of restrictions appears. Ability of large-scale thermal power plants to follow the fluctuations will soon be exhausted, and gas turbines have to be built, etc. [5, 6]. Reserves for compensating fluctuations in wind power are theoretically available only during high-load period in wintertime. Wind turbines will have remarkable power limits, especially during low-load period. Consequently, their utilisation time is less than it could be in the normal conditions. The decrease in fuel consumption in the system is small, or does not exist at all depending on the loads of the system and wind turbines. Another option is to buy balancing services from the neighbouring power systems. Also here the possibilities are limited. It is vitally important to engage small power plants (especially CHPs with heat accumulators) into the balancing of wind-power fluctuations.
4) Starting from a certain wind capacity, the balancing of wind fluctuations is possible only in co-operation with neighbouring power systems (over 250 MW in the case of Estonia). Otherwise all the positive effect of the wind energy use will be lost.

Estonian power system has quite strong links to Latvian and Russian systems. Latvia has large hydro plants, which are the main electricity producers in Latvia and important power balance regulators for the whole Baltic region and Northwest Russia, and Latvia is expanding utilization of wind energy herself as well. During the floods and dry seasons the regulation capabilities are very limited. The gigantic power system of Russia and future DC cable link to Finland will probably be the main providers of regulating power in the future, but this help will not be free of charge, of course.

The size of Estonia's territory is slightly bigger and the wind potential almost equal to the same of Denmark that also lacks hydro power, but where the installed capacity of windmills only in the Western part of the country is *ca* 2 GW. It is possible due to two main reasons:

a) Danish power system has much higher total capacity with increasing share of new natural gas power plants, which enable to absorb larger amount of wind power;
b) use of Norwegian and Swedish hydro plants for the compensation of fluctuations and also strong transmission links with the German power system.

Our analysis shows a strong correlation between the wind electricity production in Denmark and export of electricity. It is easy to conclude that the major part of wind-generated electricity has been exported [6].

An overview of limits and costs of the integration of wind turbines into the Estonian power system with the corresponding comments is given in the Table. Here the subsidies mean the difference between the probable market price of electricity and feed-in tariff of wind turbines. The table updates the information presented earlier [10].

Conclusions

In Estonia, there are very good wind resources, but there are different technical limitations on their utilization, like transmission capacity bounds of electrical network and lack of regulating reserves to compensate the fluctuations in wind power. The connection of considerable capacity of wind farms causes extensive network building and other major investments in the power system.

Involvement of thermal power plants, especially the oil shale-fired ones, in keeping the reserve capacity for wind turbines and in compensating the fluctuations of wind power substantially increases fuel consumption and emissions.

The analysis shows that the integration of considerable capacity of wind turbines in Estonia would increase fuel consumption and emissions of oil shale power stations by about 8–10%, which will reduce the environmental effect of wind turbines substantially. There can be situations where probably no environmental gain can be achieved at all.

It is vitally important to continue the discussion about both the capability of power systems to integrate large amounts of wind power and complex estimation of corresponding real environmental impact.

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