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Estimation of real emissions reduction caused by wind generators

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Abstract

The aim is to show that the fuel economy and emissions reduction in the power systems consisting mainly of thermal power plants are not proportional with the electricity production of wind turbines. Participation of thermal power plants in the compensation of fluctuating production of windmills eliminates major part of the expected positive effect of wind energy. A method for calculation of real fuel economy and emissions reduction is described and a calculation example basing on Estonian and Danish data is given.

1. Introduction

Increasing of the share of renewable energy in the electricity production 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 islands. Estonia belongs to these countries and its wind potential is remarkable.

The introduction of wind energy has been in the focus of numerous conferences, seminars and energy plans and there has been several "waves" of interest of foreign

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investors during more than 10 years. Still there is only 2 MW of wind capacity installed today in Estonia.

The wind energy projects were simply infeasible during a long period due to low electricity price in existing power system and Estonia's very limited possibilities to subsidize wind-generated electricity. In addition to that, multiple technical constraints existed as well: construction of windmills did not suite weak grids in the windy regions, absence of regulating power, needs for extensive electric network building, etc. Most of technical constraints are present also today. During last 10 years the electricity tariffs have raised several times and they continue to increase, the purchasing obligation and feed-in tariffs for electricity from renewables have written into legislation and construction of wind generators have improved substantially. This has caused recently new peak of interest in wind energy investments and even in local manufacturing of windmills to reduce the price of equipment. This interest is supported also by national target to increase the share of renewable energy in the electricity production up to 5,1% from gross inland consumption in 2010. This target was set to Estonia by European Union during the accession negotiations. The share was only 0,1% in 2001. Estonia has three possibilities to reach this heavy and expensive target: to develop biomass and wind power plants and to restore once existed small hydro plants. As the total hydro potential is only ca 30 MW, the biomass and wind have to fulfill major part of the goal.

The new "wind boom" have resulted in grid connection applications for more than 400 MW of wind capacity (ca 20% of total net capacity of existing power plants). It immediately raised questions: how many windmills can the present system integrate, what will be the costs of this expansion and what benefits can be achieved?

An interest in the development of a correct calculation method of environmental gain appeared at the Department of Electrical Power Engineering of Tallinn Technical University (TTU) already in the early 1990's, when the feasibility studies of the wind energy project proposals in Estonia used an elementary calculation of environmental effect: installed capacity of windmills was multiplied to the load factor (usually overestimated) and to the number of hours in the year, then this energy production was subtracted from the annual production of the most polluting fossil power plant unit and finally, the corresponding reduction of air pollution was found. It was obvious that the calculation cannot be so simple [1].

The accounting of emission reductions is linear also in the MARKAL model [2] that has been used by TTU in the long term planning of Estonia's energy sector and climate change studies since 1994 [3, 4]. MARKAL optimizes fuel mix and set of technologies, but it cannot consider additional emissions due to compensation of wind power fluctuations by fossil fuel power plants.

The basic concept of the methodology for calculation of the real environmental gain from wind power use was first published in Estonian language in [5] and developed further under the Estonian Science Foundation grant project [6]. Now it is time to present this methodology for wider discussion.

2. Problem of balancing of wind power fluctuations

It is well known that the wind power plants are almost uncontrollable, their power varies rapidly and frequently in 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 additional investments in the system.

A power curve of windmills of Western Denmark during one month (May 2002) is depicted in the Figure 1 and it will serve as an example of wind energy production in this paper [7].

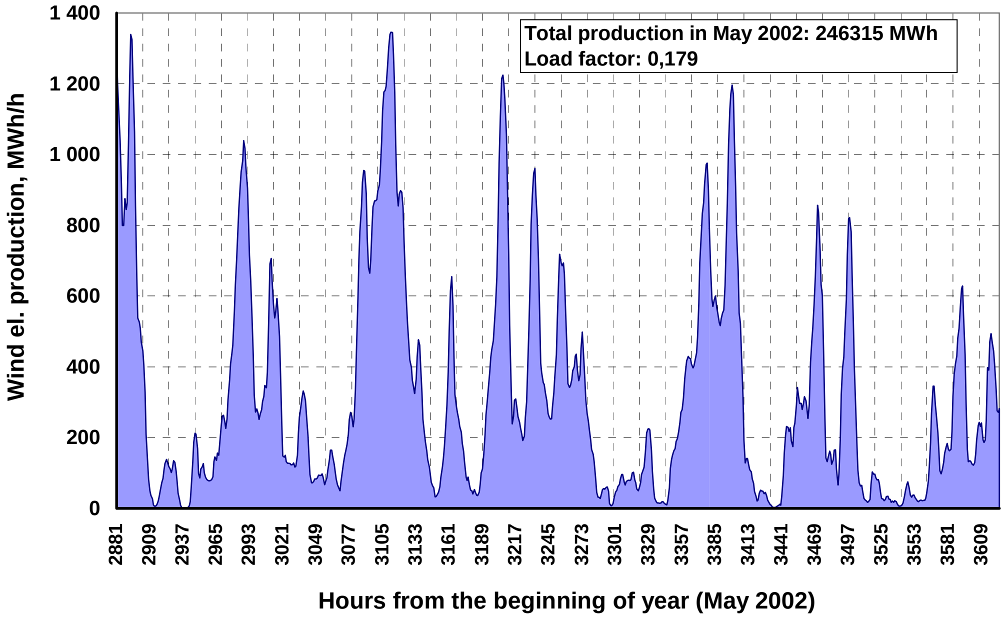

Fig. 1. Wind generated electricity production in Western Denmark in May 2002

For the reasons listed above, the integration of windmills with the existing power system is not easy. It depends on the size and structure of concrete power system and on the capacity of links with neighbouring systems. Systems that contain considerable amount of hydro power are in a favoured situation. Hydro power is controllable, fast and renewable. Until all the fluctuations of wind power can be compensated with the hydro 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 that contain only thermal power plants or if 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. Most suitable thermal plants for the load regulation and fast reserve capacity are the gas turbines. If someone wants to introduce large amount of wind power then the power regulating range and speed of the existing plants must be also extensive.

Estonian small power system is one of the world's worst systems for wind power integration. Its available net capacity is ca 2 GW containing two largest oil shale (local solid fossil fuel) power plants in the world, one large natural gas CHP, some smaller CHPs and 3,5 MW of hydro and 2 MW of wind capacity. The annual net inland electricity consumption is around 5,7 TWh (excl. losses) and exports to Latvia and Russia ca 1 TWh. Annual net electricity consumption per capita is ca 4000 kWh. Domestic peak load in wintertime reaches 1,6 GW and low load in summer decreases to 0,4 GW. The electric grids in the coastline and islands are weak. The large oil shale power plants are old and slow and they are not envisaged for the providing of regulating power. If the power of windmills remains below 10 MW, then it remains also below the sensitivity of load regulation of those big plants and no fuel consumption or emissions reduction happens. Produced wind electricity just "disappears" in the large interconnected power system of Baltic states and Russia. If the wind power increases over 10 MW, then the oil shale plants have to start compensating of the wind energy fluctuations and fuel consumption will increase. With the further increase of wind capacity a whole complex of restrictions appear (during summer low load only up to 40 MW of windmills can be switched on, ability of oil shale plants to follow the fluctuations will be exhausted soon and gas turbines have to be built, etc.) [1, 5, 6]. Estonian power system has quite strong links to Latvian and Russian systems and another option is to buy the balancing services from the neighbours. Also here the possibilities are not unlimited. Latvia has large hydro plants, but they are the main electricity producers in Latvia and important power balance regulators for the whole Baltic region and North-West Russia and Latvia is expanding wind energy itself as well. During the floods and dry seasons the regulation capabilities are very limited. The gigantic power system of Russia and future cable link to Finland will be probably the main providers of regulating power in the future, but this help will not be free of charge, of course.

The size of territory of Estonia 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 is reaching 2 GW only in the Western part of it. How is it possible?

The Danish power system has much higher total capacity with increasing share of new natural gas power plants, which enables to absorb larger amount of windmills, but the main answer is the use of Norwegian and Swedish hydro plants for the compensation of fluctuations and also strong transmission links with German power system. We analyzed the Danish wind energy data [7] and found strong correlation between the wind electricity production and export of electricity (see Figure 2). It is easy to conclude that the major part of wind-generated electricity has been exported.

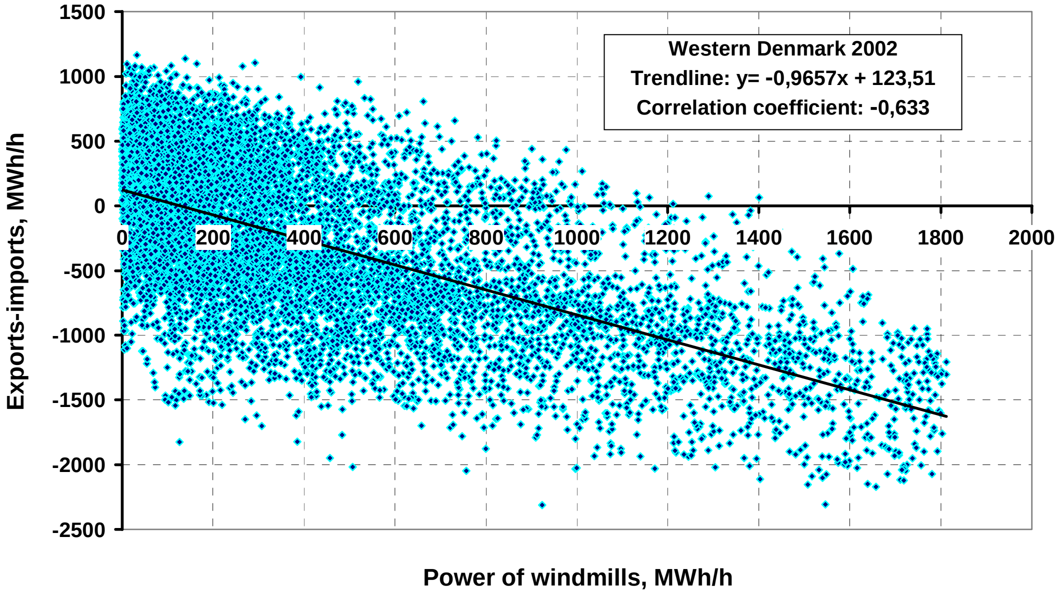

Fig. 2. Correlation between power of windmills and electricity exports-imports in Western Denmark 2002

Fast development of wind energy use 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 of wind energy expansion that have been discussed only theoretically in Estonia for a long time have become important in the countries who had developed the wind power rapidly in practice.

Let us still concentrate here only on the fuel consumption problem of thermal power plants compensating the wind power fluctuations.

Operating a thermal plant with and without the need to compensate the fluctuations of wind power is similar to the running of 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.

3. A method for calculation of environmental effect of wind power

To calculate the emissions from power system, we originate from the problem of optimal load planning.

The objective of optimal load scheduling in 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 simply the formulas, let us consider the power system that consists only of thermal plants and wind generators (e.g. Denmark or Estonia in the future). The similar situation appears also in the case of power systems that contain hydro power plants if the hydro plants cannot compensate the fluctuations of wind power.

The optimization model with discrete time can be stated as

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

subject to the following constraints:

power balance equations

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

power limitations of thermal plants

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

and spinning reserve constraints

$$\sum_{i \in I} P_{Tik}^{-} \le \sum_{i \in I} P_{Tik} - P_{W\Sigma k} \le \sum_{i \in I} P_{Tik}^{+} - P_{Rk}, \qquad k \in K, \qquad (4)$$

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

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

$P_{W\Sigma k}$ – total wind power generation 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) – (4) 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

$$b_1 = b_2 = \mu \,, \tag{5}$$

$$P_{D\Sigma k} - \sum_{i \in I} P_{Tik} - P_{W\Sigma k} = 0 \,, \tag{6}$$

and inequalities (3) where the network losses are neglected and

$b_i = \dfrac{\partial C_i}{\partial P_i}$ is the incremental cost characteristic of i^{th} power plant

and μ is a Lagrange multiplier.

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 power system due to wind energy use is calculated as the difference of emissions between optimization results with and without wind power.

In the real life, the optimization process has to be implemented under incomplete information. The main uncertainty factors in the model (1) –(4) 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 min-max 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 as the static ones.

If we deal with the necessity of compensation of wind power fluctuations with the thermal power plants, the fuel cost characteristics must be considered as the 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. Dynamic optimisation means mathematically 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 absence of necessary 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 many key input data and a need to simplify the calculation method, an easy two-step approach can be suggested:

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 characteristic to the new position and use of the new characteristic as rough substitute of the dynamic fuel consumption curve.

Let us examine the method with the help of Figure 3. It depicts the operation of a power system that consists of two power plants: equivalent thermal plant and total wind power.

a) Let assume that power system load $P_{D\Sigma k}$ is constant.

b) Line 1 depicts normal (static) fuel consumption (or cost or emissions) characteristic of equivalent thermal plant that can be used in the operation planning without wind power.

c) The thermal power production without wind generators is constant, equals to the load and it is distributed among the thermal power plants according to the equations (5) and (3) and using static characteristics.

d) When the wind power appears in the system, the thermal generation starts to vary rapidly to keep the balance of power. Wind power is characterised by the maximum total power (sum of installed capacities of all windmills multiplied by the coincidence factor) and the mean power (total installed capacity multiplied by load factor). Load factor of wind generators is calculated as the division of wind generated electricity during the considered time period by the total installed capacity of windmills.

e) Thermal power stations have to keep constantly additional spinning reserve capacity equal to the maximum total power of windmills (e.g. for the case when the too high wind speed stops full power operating windmills). This makes the thermal plants run inefficiently and increases fuel consumption (emissions).

f) Line 2 depicts the new fuel consumption (cost, emissions) curve of equivalent thermal plant that considers additional cost for keeping the reserve capacity. Values of this characteristic can be calculated with the optimal load scheduling software under different values of reserve. The point of the new characteristic that corresponds to the mean value of total wind power is depicted in the figure.

g) Most important point of the line 2 is the one that corresponds to the maximum wind power. Fuel consumption is calculated here in accordance with the objective function (1) by the optimal load scheduling software under the total load of thermal plants $\Sigma P_{Tik} = P_{D\Sigma}$ - $P_{W\Sigma\max}$ and the spinning reserve requirement that equals to the sum of the reserve value in operation without windmills P_{Rk} and the maximum total wind power $P_{W\Sigma\max}$.

h) Under the fast changes of wind power the real fuel consumption will increase even higher the line 2. The actual operation points of equivalent thermal plant will form a curve that is similar to a hysteresis loop. This is the dynamic fuel consumption curve which actual form depends on the initial operation point of the system and on the magnitude, direction and speed of change of the wind power. The actual fuel consumption (emissions) reduced to the mean value of wind power locates in the zone marked with ellipse in the Figure 3.

i) The dynamic fuel consumption (emissions) characteristic of equivalent thermal plant is reasonable to substitute by new equivalent static characteristic which is parallel to the initial curve (line 1) and lifted up by the value of additional fuel consumption (emissions) under maximum requirement of spinning reserve for compensation of wind power fluctuations.

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

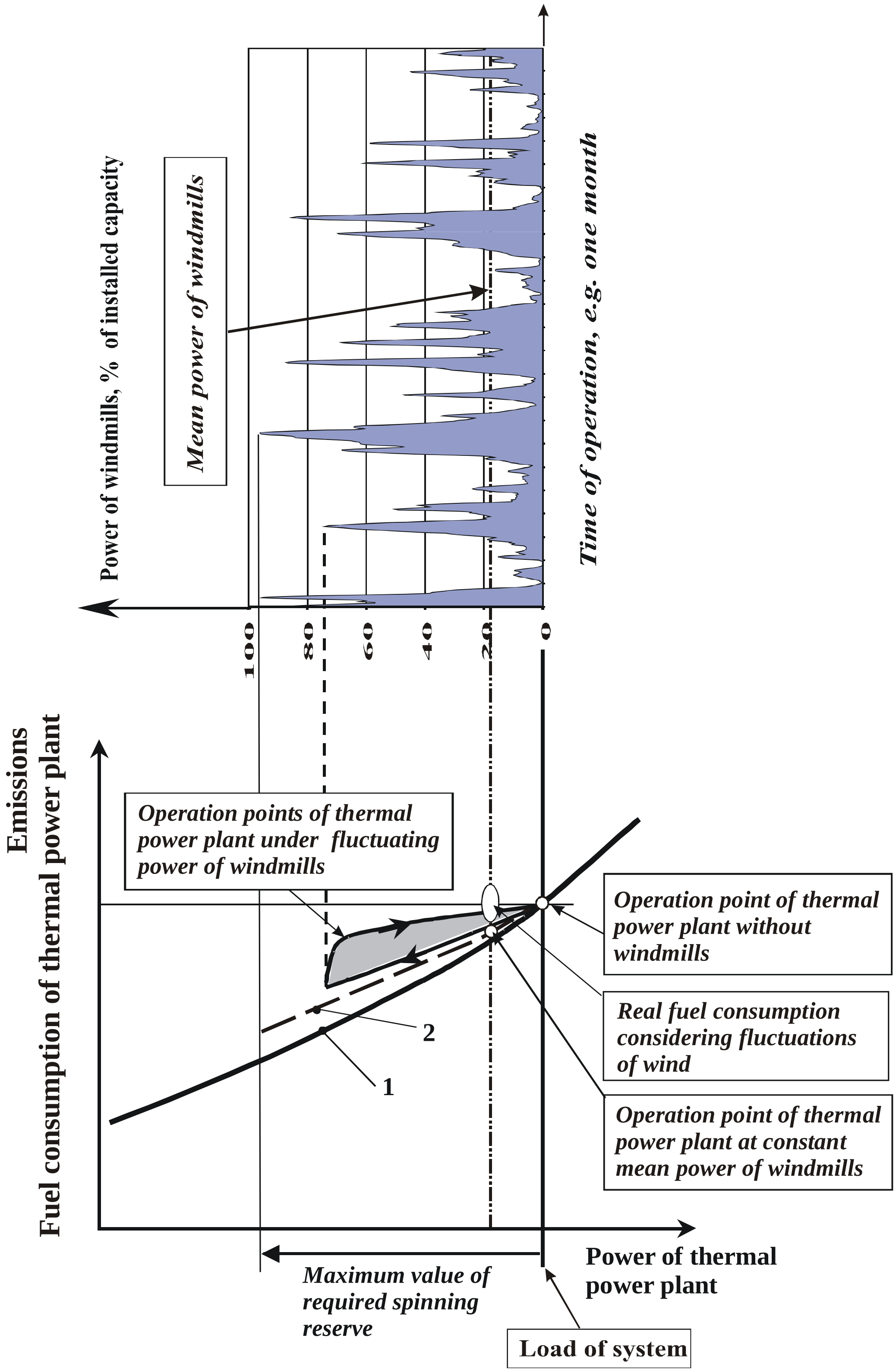

Fig.3. Explanation of wind energy balancing and fuel consumption increase problem.
1 –initial fuel consumption (or cost or emissions) curve of thermal power plant,
2 – the same curve that considers additional requirement for spinning reserve capacity due to wind generators.

4. Example

To examine the proposed above methodology, a fictional power system was composed on the base of data of thermal power plants of Estonia and wind power production of Western Denmark. The second aim of such system was to evaluate the realistic environmental gain if the wind power will be introduced in Estonia in a large scale.

The initial fuel consumption curve corresponds to the sum of Estonian thermal power plants and the wind power fluctuations represent Western Denmark in May 2002. The actual power curve of windmills was rescaled to fit the sum of the wind turbine erection applications in Estonia (400 MW).

Initial situation and calculation results are presented in the Figure 4.

If the wind turbines were ordinary controllable power plants that do not fluctuate and do not need keeping of extra spinning reserve capacity, then the normal static fuel consumption characteristics of thermal plants could be used in optimal load scheduling and 30,7% fuel consumption (emissions) reduction could be achieved under the maximum power of windmills. 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 the more realistic fuel consumption (emissions) estimate that considers also fluctuations of wind power reduced to the mean power of windmills, the initial fuel consumption curve should be lifted up also by 8,1%.

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

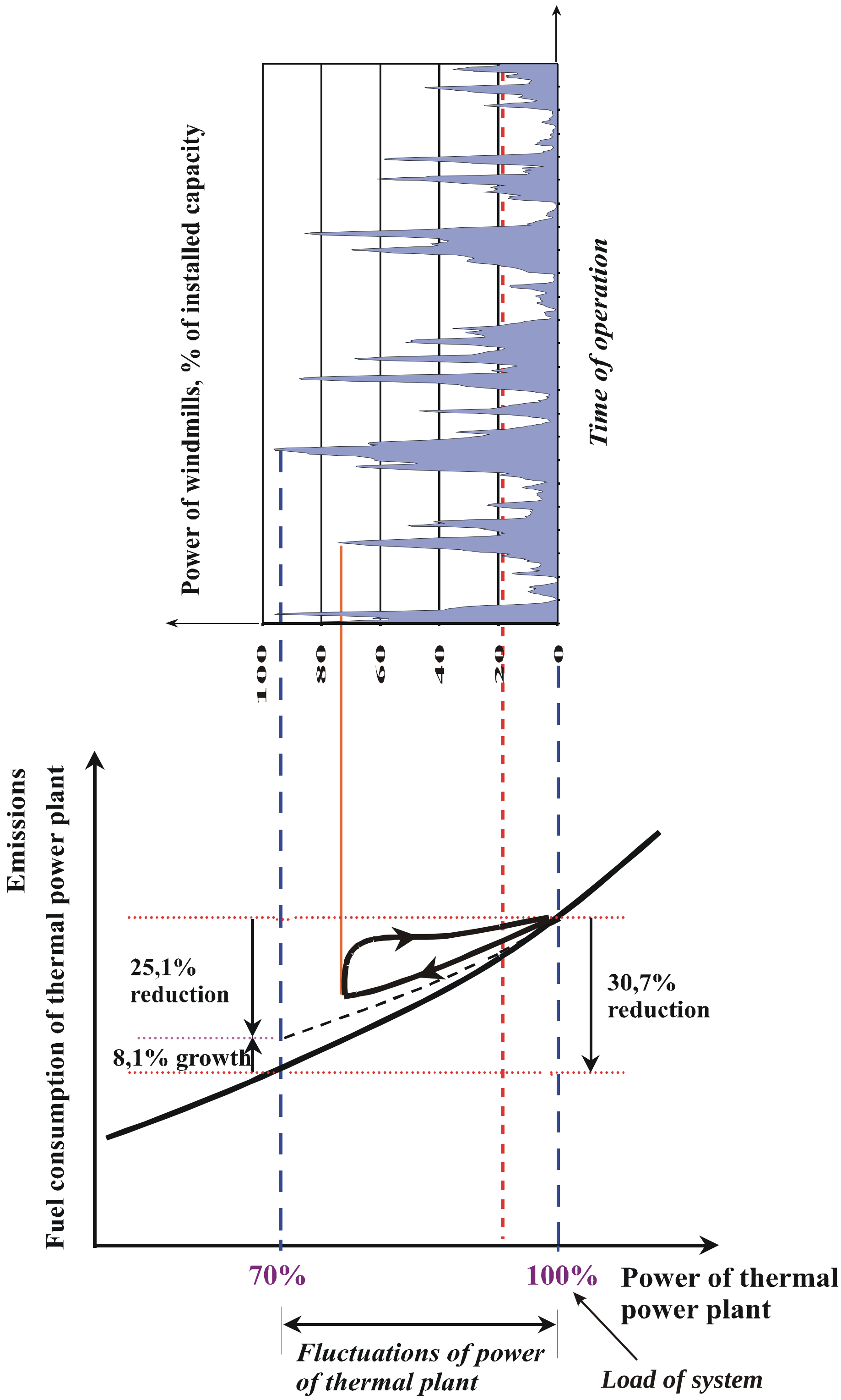

Fig. 4. Results of calculation of fuel consumption increase on the base of Estonian power system and Danish wind energy data.

5. Conclusions

Participation of thermal power plants in keeping the reserve capacity for wind turbines and in compensation of the fluctuations of wind power increases the fuel consumption and emissions substantially. Linear methods of calculation of emission reductions from wind energy use cannot consider this increase and therefore special methods for correct accounting of environmental gain have to be elaborated.

A simplified two-step method for calculation of real fuel consumption and emissions under absence of dynamic input-output characteristics of thermal power plants is proposed in this paper. Estonian case study shows that the integration of considerable capacity of wind turbines would increase the fuel consumption and emissions of thermal stations about 8-10%, which will reduce the environmental effect of windmills substantially. There can be situations where probably no environmental gain can be achieved at all.

It is vitally important to continue the discussion about the ability of power systems to integrate large amounts of wind power and to develop further the methods for the calculation of emission reductions.

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