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Energy 30 (2005) 2402–2412

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Large-scale integration of wind power into different energy systems

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Received 28 February 2004

Abstract

The paper presents the ability of different energy systems and regulation strategies to integrate wind power. The ability is expressed by the following three factors: the degree of electricity excess production caused by fluctuations in wind and Combined Heat and Power (CHP) heat demands, the ability to utilise wind power to reduce CO_2 emission in the system, and the ability to benefit from exchange of electricity on the market. Energy systems and regulation strategies are analysed in the range of a wind power input from 0 to 100% of the electricity demand. Based on the Danish energy system, in which 50% of the electricity demand is produced in CHP, a number of future energy systems with CO_2 reduction potentials are analysed, i.e. systems with more CHP, systems using electricity for transportation (battery or hydrogen vehicles) and systems with fuel-cell technologies. For the present and such potential future energy systems different regulation strategies have been analysed, i.e. the inclusion of small CHP plants into the regulation task of electricity balancing and ancillary grid stability services and investments in electric heating, heat pumps and heat storage capacity. The results of the analyses make it possible to compare short-term and long-term potentials of different strategies of large-scale integration of wind power.

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1. Introduction

Large-scale integration of wind power into the electricity system needs to address the challenge of designing integrated regulation strategies of overall energy systems. The wind turbines need to interact

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0360-5442/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.energy.2004.11.001

with the rest of the production units in the system in order to make it possible for the system to secure a balance between supply and demand. The challenge becomes even harder if wind power investments are combined with other types of improvements in the systems, such as CHP and better efficiencies. Furthermore, such strategies benefit from including potential trade on the international electricity market in the analyses.

The integration of wind power has been analysed thoroughly with focus on stand-alone systems and the integration of fuel cells and hydrogen systems [1–8]. Similar analyses have been made of the balancing of CHP electricity productions with restrictions in biomass fuels, grid connections and consumer demands [9–12]. Also demand side management is well-described including analyses of the influence on demand distribution, such as peak load reduction or flexible demands [13–15].

Meanwhile, there is a growing trend towards distributed electricity production and supply in Europe [16–22]. Both increased decentralised production and the use of wind power will result in a growing number of small and medium size producers, who will be connected to energy networks and in particular to electricity grids, which are originally designed for monopolistic markets. Therefore, many new problems will arise, in relation to management and operation of energy transfer as well as in relation to efficient distribution of wind power and other renewable energy sources in the grids [23–25].

In order to bring about a substantial long-term penetration of distributed energy resources in Europe, it is necessary to address the key issues related to their integration into existing and future energy systems. One of the most important future challenges seems to be the management of the integration of fluctuations in the electricity production from renewable energy sources and the electricity production from CHP units.

Danish Energy Policy has succeeded in stabilising primary energy supply during a period of 30 years. Insulation of houses and an extensive expansion in the use of CHP has led to decrease in fuel consumption for domestic heating. This was achieved during a period of 30 years of economic growth, in which the number of houses increased. Additionally, different types of renewable energy have been introduced and strongly supported by the government [26–29]. Today, wind power produces almost 20% and CHP 50% of the electricity demands [30]. Consequently, Denmark is leading, in terms of integrating distributed production into the national electricity production system.

Based on the Danish case, this paper presents the results of analysing large-scale integration of wind power into different energy systems using different regulation strategies. The different alternatives are evaluated on the following three qualities:

- The ability to avoid excess electricity production.
- The ability to utilise wind power to reduce domestic CO_2 emissions.
- The ability to exploit trade on the international Nord Pool electricity market.

2. Methodology

The problem of large-scale integration of wind power has been analysed by modelling the western Danish energy system in year 2020 on the EnergyPLAN computer model. At the start the system has been analysed on the basis of the present regulation of CHP plants (reference *regulation* system) and in the present combination of CHP, DH (District Heating) plants, etc. (reference *energy* system).

Different alternative *regulation* and *energy* systems, including different investments in improving the flexibility, have been subject to both a technical and an economical analysis. The technical analysis has compared the different systems on their ability to integrate wind power expressed in terms of ability to reduce excess electricity production and the domestic CO_2 emission. The economical analysis has compared the systems' ability to exploit trade on the Nord Pool market.

2.1. The EnergyPLAN model

The EnergyPLAN model is an input/output model (see Fig. 1). General inputs are demands, capacities and the choice of a number of different regulation strategies, putting emphasis on import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption and import/exports.

The energy system in the EnergyPLAN model includes heat production from solar thermal, industrial CHP, CHP units, heat pumps and heat storage and boilers. District heating supply is divided into three groups of boiler systems and decentralised and centralised CHP systems. Additional to the CHP units the systems include electricity production from renewable energy, i.e. photovoltaic and wind power input divided into onshore and offshore, as well as traditional power plants (condensation plants).

The model requires four sets of input for the technical analysis. The first set is the annual district heating consumption, and the annual consumption of electricity, including flexible demand and electricity consumption from the transport sector, if any. The second set is the capacity of photovoltaic and wind power, including a moderation factor, in order to adjust the relationship between the wind capacity and the correlating electricity production. Also this part defines solar thermal, industrial CHP heat production inputs to district heating. The third set is capacities and operation efficiencies of CHP

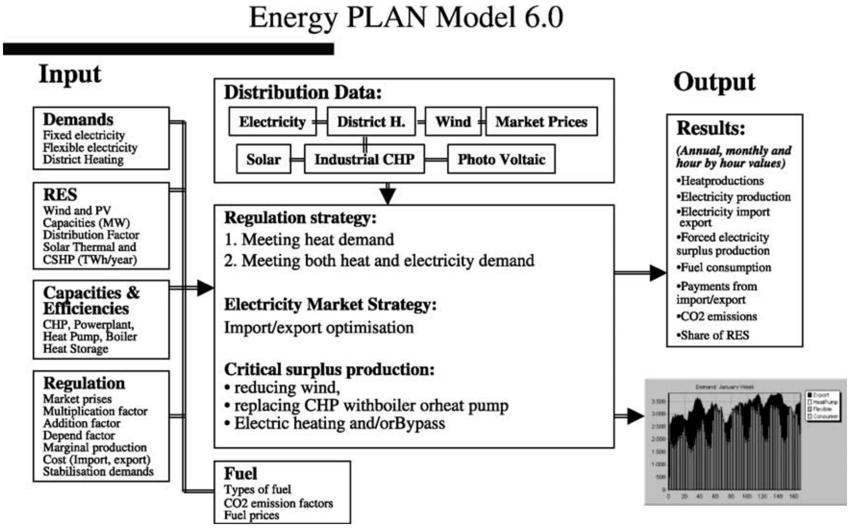

Fig. 1. The EnergyPLAN Energy System Analysis model.

units, power stations, boilers and heat pumps. And the last set specifies some technical limitations; namely the minimum CHP and power plant percentage of the load in order to remain grid stability. Furthermore, it includes the maximum heat pump percentage of the heat production, in order to achieve the specified efficiency of the heat pumps.

For the economic calculations of exporting and/or importing electricity, the model needs input to define price variations on the international electricity market. The model has an internal hour by hour standard price variation based on the first operation year of the Nord Pool market. These price variations can be adjusted by the following inputs: a multiplication factor, an addition factor (DKK/MWh) and an adjustment price of non-predictable export/import. Moreover, a factor expressing market-reactions to wind and CHP can change the market. Furthermore, input is needed in terms of marginal production fuel costs and costs of 1 MWh electricity produced, when heat, produced by either boilers or heat pumps, is replaced by heat produced by CHP.

The model emphasises the analysis of different regulation strategies. Basically, the technical analyses distinguish between the two following strategies:

Regulation strategy I: meeting heat demand. In this strategy all units are producing solely according to the heat demands. In district heating systems without CHP the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are given priority according to the following sequence: solar thermal, industrial CHP, CHP units, heat pumps and peak load boilers.

Regulation strategy II: meeting both heat and electricity demands. When choosing strategy II, export of electricity is minimised mainly by replacing CHP heat production by boilers or by the use of heat pumps. This strategy increases electricity consumption and decreases electricity production simultaneously, as the CHP units must decrease their heat production. With the use of extra capacity at the CHP plants combined with heat storage capacity, the production at the condensation plants is minimised by replacing it with CHP production.

In the economical analysis the two strategies mentioned above are moderated by a market trade strategy based on the principle of exporting whenever the market prices are higher than the marginal production costs and importing whenever the market prices are lower than the marginal production costs.

In all strategies the model takes a number of restrictions and limitations in to consideration, such as:

- the system needs a certain degree of grid-stabilising capacity
- bottlenecks in transmission capacity
- strategies for avoiding critical excess production
- maximum percentage of heat production from heat pump.

For a detailed description of the model, please consult [31,32].

2.2. Reference energy system

The western part of Denmark year 2020 has been chosen as a reference scenario. The region is identical to the area of the transmission system operator: Eltra. This reference scenario is based on the ELTRA system plan 2001 and was used in the work of an expert group, which in year 2001, on request of the Danish Parliament, investigated the problem of large-scale integration of wind and analysed possible means and strategies for managing the problem [33]. As part of the work, Aalborg University made some long-termed year 2020 energy system analyses of investments in more flexible energy systems in Denmark [34,35].

The reference was constituted by the following development: the Danish electricity demand was expected to rise from 35.3 TWh in year 2001 to 41.1 TWh in year 2020 equal to an annual rise of approximately 0.8%. The installed capacity of wind power in year 2001 was expected to rise from 570 to 1850 MW in East Denmark and from 1870 to 3860 MW in West Denmark in year 2020. The increase is primarily due to the implementation of one 150 MW off shore wind farm each year. Existing large coal-fired CHP steam turbines are replaced by new natural gas fired combined cycle CHP units when the life of the old CHP plants expires.

2.3. Reference and alternative regulation systems

The reference regulation system has been defined as the present regulation adjusted by a number of likely measures to avoid critical excess production. Thus the reference regulation can be described in the following way:

- All wind turbines produce according to the fluctuations in the wind
- All CHP plants produce according to the heat demand (or the triple tariff)
- Solely the large power stations participate in the task of balancing supply and demand and securing grid stability
- Minimum 300 MW and minimum 30% of the production must come from grid stabilising power stations
- Critical excess is avoided by using the following priorities: (1) replacing CHP with boilers, (2) using electric heating and (3), if necessary, stopping the wind turbines.

The ability of the reference system to integrate wind power has been compared with a number of alternative regulation systems based on the following principles:

- CHP units operate in order to integrate wind power by reducing their electricity production in hours of excess production. Instead a boiler, and/or electric heating, and/or a heat pump replace the heat production.
- Small CHP units are included in the grid stabilisation task.

3. Results of technical analysis

All the analyses have been carried out for a wind power input from 0 to 25 TW h equal to a variation from 0 to 100% of the electricity demand in the reference (24.87 TW h).

The results of the reference *energy system* with the reference *regulation system* are shown in Fig. 2. The upper diagrams show the excess production and the domestic CO_2 reduction in a situation without any limits in the transmission capacity (open system). In the two diagrams below the same results are shown in the case of the existing capacity limit (1700 MW limit) and in the case of no transmission capacity at all (closed system).

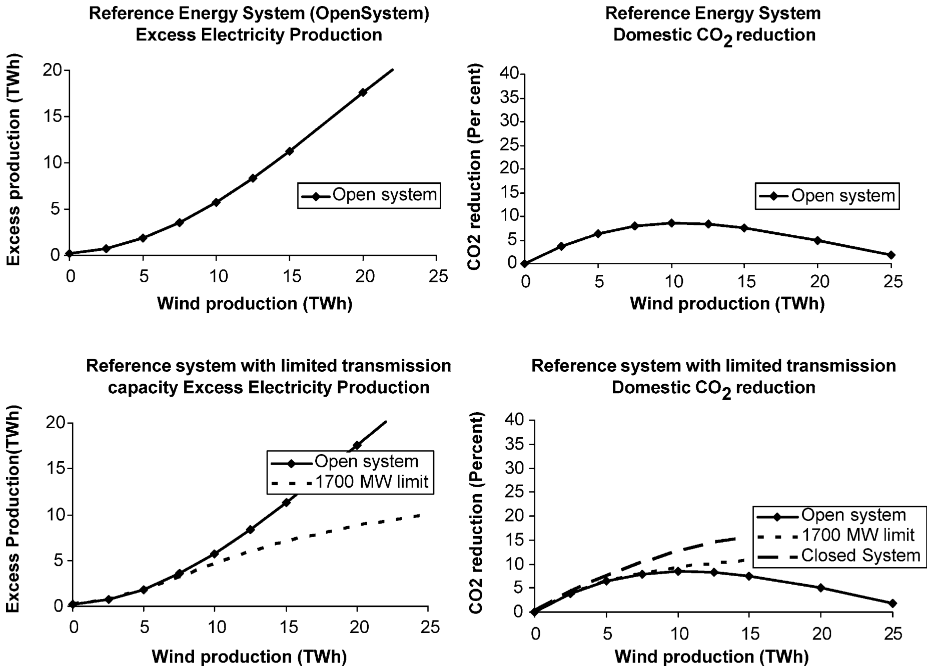

Fig. 2. Excess electricity production and domestic CO_2 reduction in the reference energy system with the reference regulation system.

As illustrated such a system has considerable problems in utilising wind power inputs. For example the excess production is as high as 2 TWh for a wind input of 5 TWh, and the excess increases to 6 TWh if the wind production is 10 TWh. Consequently the utilisation of wind power for CO_2 emission reductions is becoming weaker and weaker when increasing inputs. Already at 10 TWh the domestic emission is starting to increase again. This is due to the increased need for grid stabilisation from large power plants.

The excess production can be avoided by replacing CHP production with boilers and electric heating or stopping wind turbines. But as illustrated the ability to reduce CO_2 emission is then showing a very poor result.

Naturally, the resulting excess production and CO_2 reduction are very sensitive to the definition of the energy system. And CO_2 reduction policies are likely to lead to changes in the future system, which influences the results. Consequently, the above analysis has been carried out for the three following alternative energy systems, which all represent further improvements in relation to making domestic CO_2 reductions in the Danish system:

50% more CHP: In the reference system 21.21 TWh equal to app. 50% of the heating is produced in CHP. An alternative system has been defined in which the share of CHP is increased by 50% to 31.82 TWh.

Fuel cell technology: Improvements of electric efficiencies in the CHP units and Power Plants (as for example fuel cells) increase the efficiency and consequently decrease the fuel consumption.

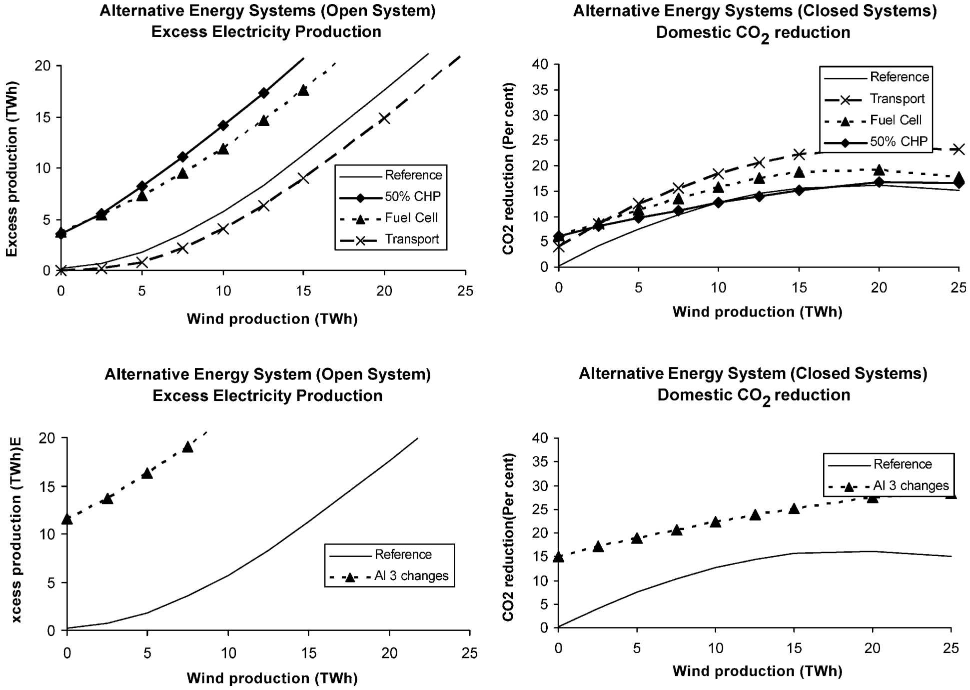

Fig. 3. Excess electricity production and domestic CO_2 reduction in the three alternative energy systems with the reference regulation system. Above the three alternatives are shown individually and below in combination.

An alternative system has been defined by raising CHP efficiencies from average 38 to 55 and power plant efficiencies from 50 to 60%.

Electrification of cars: Based on a study of electrification of cars (partly battery and partly hydrogen fuel cell vehicles) an alternative system has been defined in which 12.56 TWh of petrol can be replaced by 4.4 TWh of electricity [36].

The results of the analyses of the alternative systems are shown in Fig. 3. The diagram illustrates how improvements in terms of more CHP (‘50% CHP’) and better efficiencies (‘fuel cell’) accelerate the excess production problem, while the electrification of cars (‘transport’) decreases the problem. In the starting point without any wind power all the improvements decrease CO_2 emissions compared to the reference energy system, but along with increasing wind input only the electrification of cars maintain the better CO_2 reduction ability.

Fig. 4 shows the same results, if alternative regulation systems are introduced. It shows how important it is to include the CHP units in the regulation. Such measure alone decreases the excess production radically both in the reference and in the alternative energy system. Meanwhile, if the CHP units are replaced by boilers (CHPregB) the fuel efficiency is decreased and the potential for CO_2 reductions are not fully exploited. Adding electric heating to the system (CHPregEH) does not solve the problem, but adding Heat Pumps (CHPregHP) makes it possible to decrease excess production and at the same time maintain fuel efficiencies.

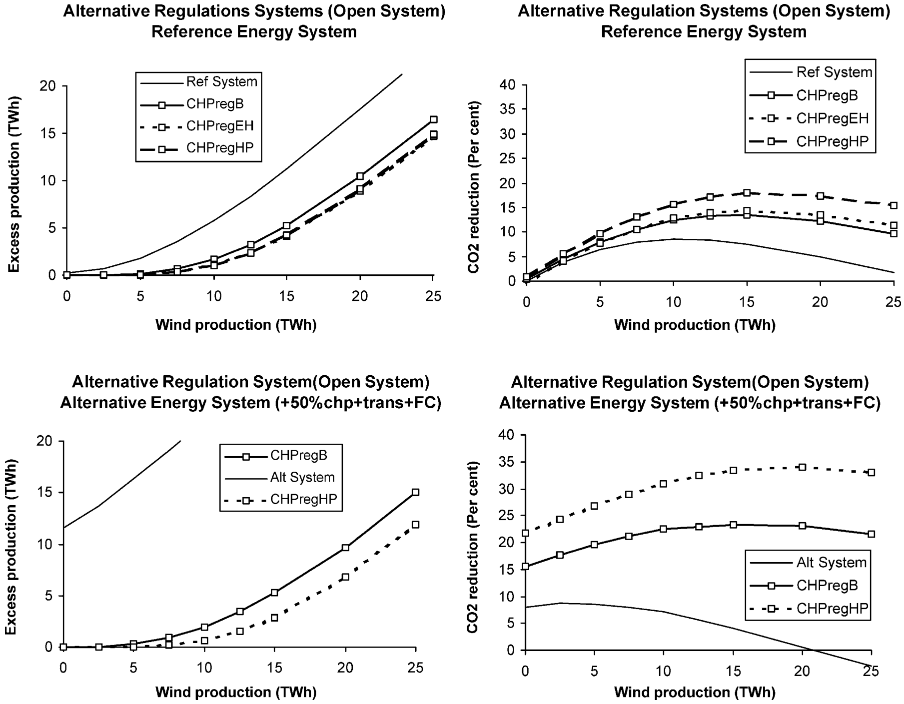

Fig. 4. Excess electricity production and domestic CO_2 reduction in alternative regulation systems. Above three alternative regulation systems are shown in the reference energy system and below in the alternative energy system (50% chp + transp. + FC).

Also the consequences for the transmission grid has been analysed in the project. Meanwhile, the results are not included in this paper. Preliminary results have been published in [23].

4. Results of economical analysis

The feasibility of the flexible energy systems has also been evaluated on its ability to exploit the Nord Pool market.

The modelling of the Nord Pool market has been based on the following considerations:

- The hour by hour price standard distribution based on historical data from the first few years of operation. The standard distribution has a mean value of 140 DKK/MWh and represents a wet year with plenty of water in the Nordic hydro plant systems.
- An influence on the Nord Pool price of 0.02 DKK/MWh per MW Danish Trade based on analysis of historical data.
- A 7 year period of one Dry year, three Wet years and three normal years created out of the standard price distribution in such a way that the mean value of the future years from 2010 to 2020 equals the expectation of the Danish Energy Agency (240 DKK/MWh)
- Influence of trade with Germany described as fixed import/export hour distributions based on typical trade in years with high or low prices on Nord Pool.

– Splitting of the market into price areas if bottleneck arises in the transmission system.
– Fossil fuel prices according to the expectations of the Danish Energy Agency.

For such a market model the trade has been analysed for international CO_2 trade prices between 0 and 250 DKK/t CO_2 and for wind production prices between 170 and 270 DKK/MW h.

It has been analysed whether investments in new power plant capacities are feasible in such a system. The result is that the possibilities of increasing the profit of trading are very limited and the additional income is far from being able to pay back the investment.

Meanwhile, investments in flexible energy systems seem to be very profitable. Two of the alternative regulation systems already analysed above, namely ‘including the CHP units in the regulation’ and replacing heat production either by boilers (CHPregB) or by Heat Pumps (CHPregHP) are of special importance. When the wind power on an annual basis exceeds 20% of the electricity demand it becomes very feasible to invest in such solutions, especially the heat pumps. Thus, the feasibility of heat pumps (after paying for investment costs) is approximately 10 million EUR/year for 20% wind power increasing to 80 million EUR/year for 60% wind power. Such feasibility is to be compared to annual investment and fixed maintenance costs of only 15 EUR/year. Consequently the investment has an interest of between 50 and 500% depending on the share of wind power. All the analyses have been based on the same heat pump capacity. Meanwhile, such capacity is likely to be adjusted and optimised to the actual wind power input, in which case the feasibility of the investment can be improved further [37].

5. Conclusions

Until now, the task of balancing electricity supply and demand has been left primarily to large production units. Small CHP plants and wind turbines have not been involved in the regulation. Consequently, the ability to large-scale integration of wind power in the Danish system, which is characterised by a high degree of CHP, is very weak. The percent of excess electricity production is relatively high, and the ability to utilise wind to reduce domestic CO_2-emissions is low.

If Denmark were to increase the percent of wind power to 50% as planned, the problems would become severe. If, at the same time, Denmark were to increase the degree of CHP and improve operation efficiencies the problems would become even worse.

This article has presented the results of implementing flexible regulation systems such as including the CHP units in the regulation and eventually investing in heat pumps. Such systems have been evaluated both on their ability to avoid excess production in the system and on their ability to exploit trade on the international electricity market.

The feasibility of such improvement in flexibility is very high, and can be recommended for any percent of wind power, especially wind inputs above 20–25%.

Acknowledgements

The findings in this article result from two research projects at Aalborg University, which have been supported financially by the Danish Energy Agency and by the Danish Energy Research Programme. The results were presented and discussed at the Fourth International Workshop on Large-Scale

Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Billund 20–21 October 2003.

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