Technical Design of Flexible Sustainable Energy Systems

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ABSTRACT

Today, electricity in most countries is produced either on hydropower or on large steam turbines based on fossil fuels and nuclear power. Electricity from distributed generation only constitutes small amounts. And until now, the task of balancing supply and demand and the task of securing frequency and voltage on the grid has been left solely to large production units.

Meanwhile, the implementation of cleaner technologies such as renewable energy, combined heat and power production (CHP) and energy conservation is necessary for future sustainable energy systems. Consequently such distributed production units sooner or later need to contribute to the task of securing a balance between electricity production and consumer demands.

Already now, Denmark is facing this problem. An active Energy Policy has reduced burning of fossil fuels and CO_2 emissions by expanding wind power and small CHP units. And today, on a national average, more than 30 per cent of the electricity production is coming from such small production units. In the western part of Denmark, the figure is even above 40 per cent.

This paper presents technical designs of potential future flexible energy systems, which will be able both to balance production and demand and to secure voltage and frequency requirements on the grid.

INTRODUCTION

European Energy Policies have given priority to the fight against global warming. Both energy efficiency and the development of new and renewable energy technologies are considered key elements in the change. Thus replacement of boilers and power stations with CHP-units and an increase in the share of RES in the energy supply are objectives to the European Union. The latter includes increasing the part of RES in electricity production from 14 per cent to 22 per cent to be attained before year 2010 [1]. A Directive on RES has already been agreed upon [2] and a Directive on CHP has been proposed.

The implementation of such policies result in an increased share of distributed generation. And the share in some areas and regions is likely to be much higher than the average. For instance the objective of increasing the average share of RES electricity production to 22 per cent is distributed among the EU member states resulting in RES percentages between 6 per cent to 78 per cent. Large hydro power plants are included in the plan, but also the expansion of distributed

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generation is important for fulfilment of the objective. Research studies indicate that the least cost fulfilment of the objective might call for even higher differences than proposed in the directive, since some member states have better possibilities of fulfilling their share than others [3].

Meanwhile large-scale integration of RES and distributed generation raises the problem of finding balance between electricity demand and production. And EU targets for the deployment of CHP and renewable energy will only be achieved if this balance can be found in most, if not all, EU states, and in the EU Accession States.

If the balancing problem can be effectively overcome then the EU can proceed towards its targets for, on the one hand, liberalised electricity markets and, on the other, 22 per cent of electricity production from renewable energy to be attained before year 2010.

ELECTRICITY BALANCING AND GRID STABILITY

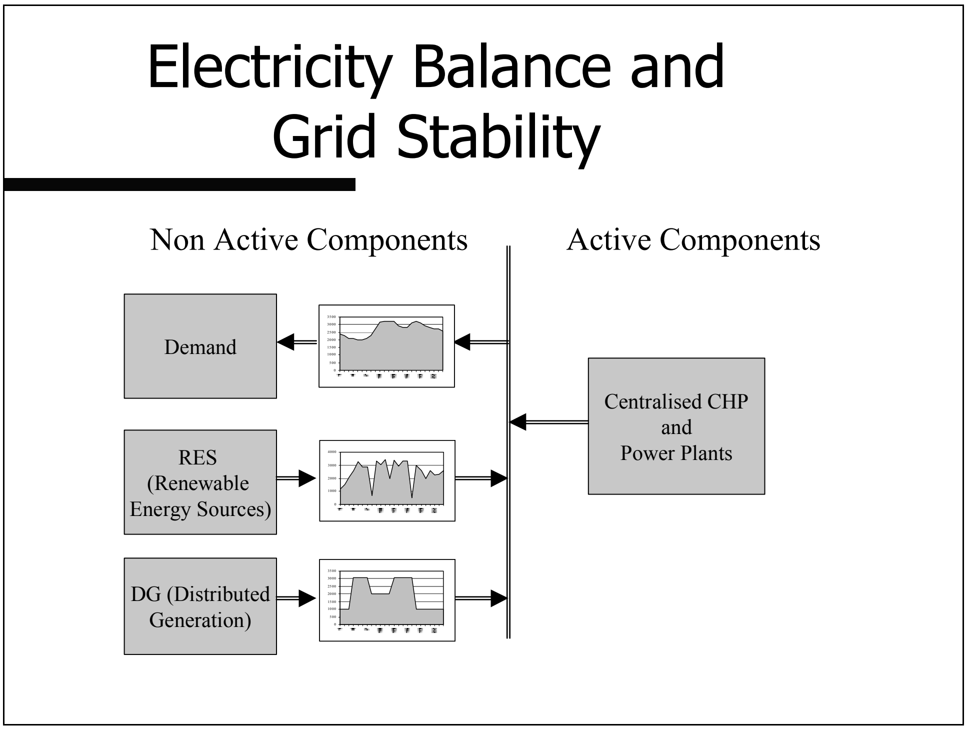

Figure 1. Existing Electricity System in Denmark

Figure 1 illustrates the principle of securing a balance between supply and demand and securing grid stability. Until now, the task of securing a balance between electricity production and consumer demand has been given solely to large power plants. However, small- and medium sized CHP plants can be used to balance fluctuating outputs from wind turbines. The ongoing effort to liberalise electricity markets has major implications on the integration of both CHP and fluctuating renewable energy sources. For instance the rules of the NordPool system discourage small-scale CHP plants from taking part in balancing the power production. However, the small-scale CHP units have the technical potential to solve some of the balancing problems if they can be technically linked to a specific wind power development.

In Denmark small- and medium scale CHP plants are not participating directly in balancing wind power. Meanwhile these plants are participating in balancing fluctuations in the demand. The CHP plants have been paid through a triple tariff system with high payment between morning and late afternoon, reflecting a high electricity demand during this period, and low payment during night hours, weekends and holidays. Consequently, the Danish CHP has been designed with relatively high capacities of the CHP unit and with heat storage making it possible to produce mainly during the high tariff period. When electricity sales prices are high, the CHP unit operates full capacity and store heat in the heat storage. When prices are low, the CHP units stop and heat for district heating is supplied from the storage. So far this regulation ability has not been used to integrate fluctuations in renewable energy.

The small CHP units can be used to 'balance' the fluctuating output of wind power projects, which can cause problems for electricity systems. The heat storage facilities of the CHP plant are important in this technique because CHP plant can increase electricity production when and if required for balancing activities without economic penalty provided surplus heat production can be stored for future use.

In the existing Danish system both tasks are solved primarily by the large power plants. In some countries large hydro power plants take part in fulfilling the task as well. When the share of distributed generation is small the security will not be compromised. But when the share increases situations will appear in which security might be compromised and the system design consequently has limits to the integration of CHP and RES. In figure 1 small and medium CHP plants are illustrated as distributed generation operating in accordance with a fixed triple tariff.

REFERENCE SCENARIO

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.

In Denmark renewable energy sources and distributed generation have been prioritised in the Energy Policy for several years [4]. Thus today, approximately 15 per cent of the electricity demands are produced on wind power, and approximately 50 per cent are produced in CHP including both large stations in the cities and distributed plants in the small towns and villages. Even now the electricity production from wind turbines and CHP results in "surplus production" problems in the western part of Denmark as wind power production depends on fluctuations in wind, and CHP depends on heat demand. And the problem will increase along with the growing number of wind turbines and CHP plants.

The surplus production problem is a challenge in the light of the overall surplus situation as well as a challenge in relation to the interaction with the international market for electricity. Consequently, in 2001, on request of the Danish Parliament, the Danish Energy Agency formed an expert group to investigate the problem and analyse possible means and strategies for managing the problem [5]. 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 [6].

The expert group defined a reference scenario showing the development in both critical and exportable surplus production if expansions in CHP, wind power and demands were to be implemented according to the official policy. Three years, namely 2005, 2010 and 2020 were chosen for the analysis. The Danish electricity system is divided into two separate geographical areas: east and west Denmark. Surplus electricity production can increase in one area without consequence for the other, and it was thus necessary to analyse each area separately.

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 per cent.
- 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 lifetime of the old CHP plants expires. Additionally, distributed CHP plants and industrial CHP's are due to a small expansion.

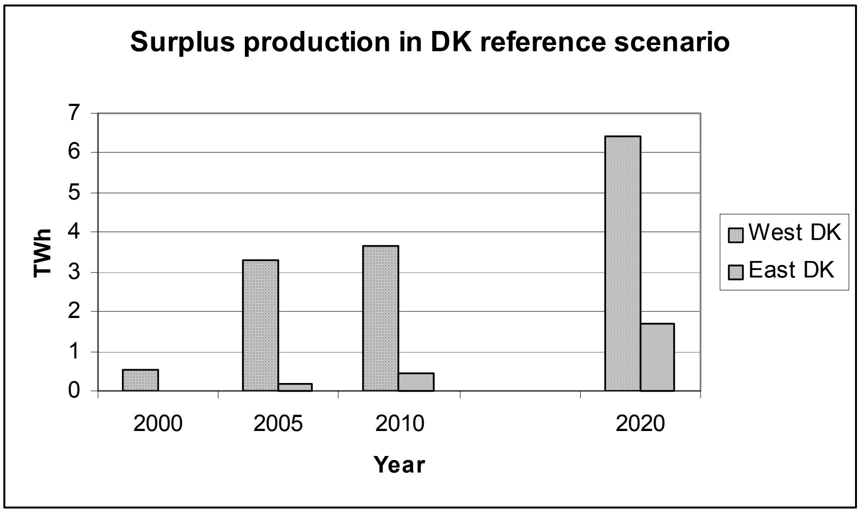

Figure 2: Surplus electricity production in DK reference scenario [5].

Based on the assumptions mentioned above, the expert group evaluated the magnitude of the expected surplus production problem. The result of the analysis is shown in figure 2. As shown the surplus production, in the reference scenario is expected to increase considerably in the period towards year 2020. The expected surplus production of 1680 GWh in east Denmark equals 11 percent of the demand in year 2020. In west Denmark the surplus equals 28 per cent. The fact that expectations to the magnitude of the surplus production are as high as illustrated in figure 2 can be explained especially by the following two presumptions:

First, the small and medium scale CHP plants are not expected to regulate according to fluctuations in wind power, but solely according to heat demands.

Secondly, the task of securing grid stability (voltage and frequency) has been given solely to large power stations. Consequently, distributed production from small CHP units and the wind turbines are considered a burden to the fulfilment of this task.

DESIGN OF POTENTIAL FUTURE TECHNICAL SYSTEMS

In order to identify limits and possible solutions of increasing the share of RES and CHP, three potential future systems have been analysed and compared with the existing system. The systems are illustrated in figure 3.

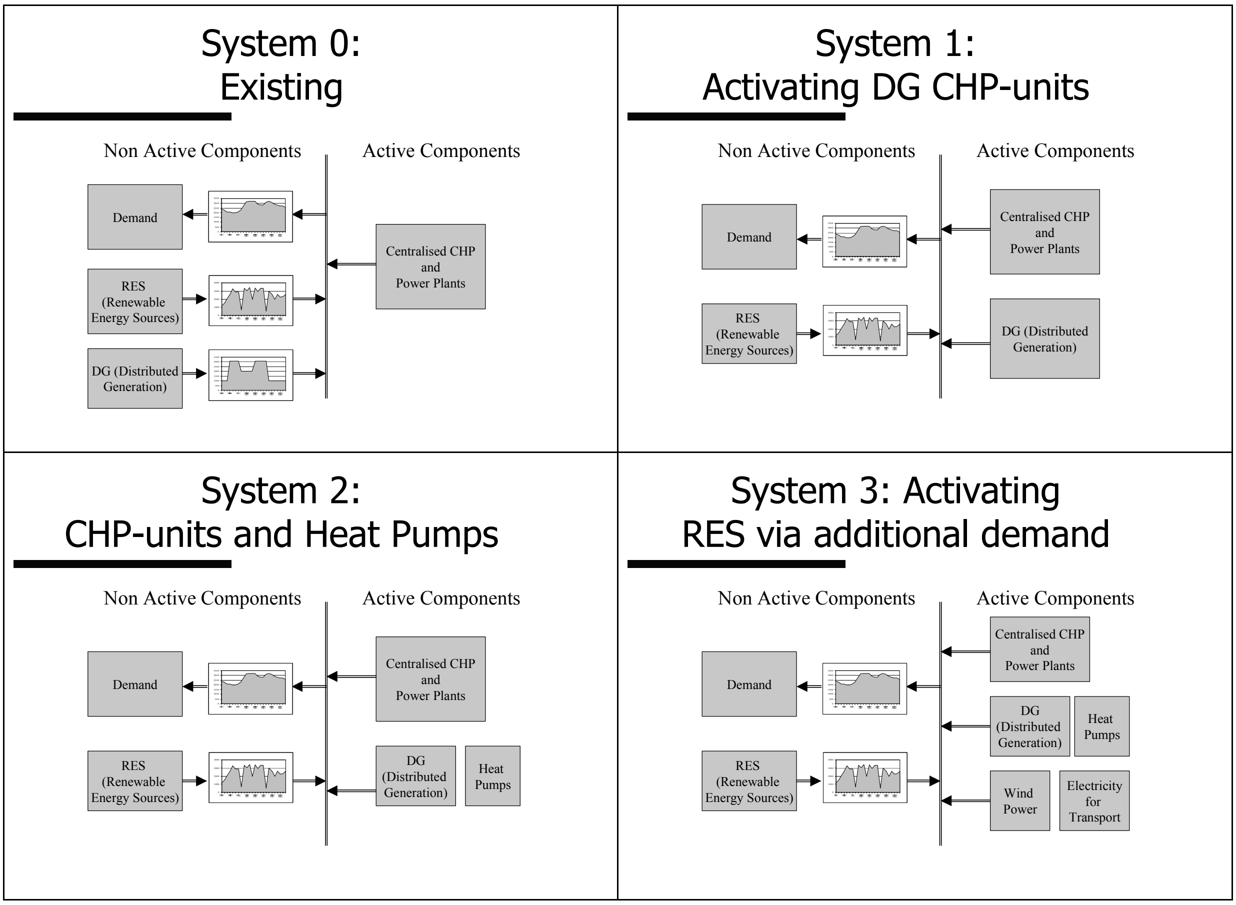

Figure 3. Different system designs for large-scale integration of RES

<u>*System 0 (Reference)*</u> is characterised by the following:

- Distributed generation units are operating according to fluctuations in the heat demand during the season and a fixed triple tariff during a period of a week.
- RES (i.e. wind power) are operated according to fluctuations in the wind
- Centralised Power Stations including CHP are operated in order to secure a balance within the limits of producing in accordance with the fluctuations in district heating demand during the season.
- The task of securing frequency and voltage is left solely to the centralised units, constituting the restriction that the production from these units must always be at least 30 per cent of the total electricity production. And the production must always be at least 350 MW (in order to have the necessary units rolling).

This system is representing the present system in Denmark.

<u>*System 1 (Activating small- and medium scale CHP plants):*</u> The system is the same as the reference apart from all the CHP plants being operated in order to balance both heat and electricity production. If the electricity production exceeds the demand parts of the CHP units

are replaced with boilers. The heat storage capacities are used to minimise such replacement. The system has been analysed both in a situation in which small- and medium scale CHP plants are not participating in the grid stabilising task (System 1A) and in a situation in which they are (System 1B).

System 2 (Adding heat pumps): In system 1, CHP production is replaced by heat production from boilers, and consequently the fuel efficiency is decreased. The idea of system 2 is to compensate the increase in fuel consumption by adding heat pumps to the system. Furthermore heat pumps increase the flexibility because they can be used to consume electricity in hours of surplus production and at the same time replace heat production from CHP units. Again the system has been analysed both in a situation in which the small plants are not participating in the grid stabilising task (System 2A) and in a situation in which they are (System 2B)

System 3 (Including electricity for transportation): In system 3 electricity consumption for transportation is added to the regulation system according to a scenario described by the Risø National Laboratory [7]. Vehicles that weigh less than two tons are transformed into a combination of battery vehicles and hydrogen fuel cell vehicles. In year 2015 4,92 TWh of oil is replaced by 1,6 TWh of electricity, and in year 2030 20,83 TWh oil is replaced by 7,3 TWh. Based on this national scenario it has been chosen to analyse a scenario for western DK in which 3,2 TWh electricity substitutes 9,84 TWh oil year 2020. The distribution of the electricity consumption is the same over the year, but can be placed freely with 50 per cent within the period of a day and 50 per cent within the period of a week with respect to a limit in capacity of the batteries and the hydrogen production unit.

METHODOLOGY

The different regulation systems have been analysed on the energy system analysis model EnergyPLAN. The model is an input/output model. General inputs are demands, capacities and the choice of a number of different regulation strategies, putting emphasis on import/export and surplus production of electricity. 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 categories: I) group of boiler systems, II) group of decentralised CHP systems, and III) group of centralised CHP systems. Additional to the CHP units the system includes electricity production from renewable energy, i.e. photo voltaic and wind power input divided into onshore and offshore, as well as traditional power plants (condensation plants).

The main purpose of the EnergyPLAN energy system analysis model is to design suitable national energy planning strategies by analysing the consequences of different national energy investments [8].

The model emphasises the analysis of two different regulation strategies. In strategy I, all units are produced solely according to the heat demand. The units are given priority according to the following sequence: Solar thermal, industrial CHP, heat plant CHPs, heat pumps and peak load boilers. In regulation strategy II, export of electricity is minimised mainly by the use of heat pumps at combined heat and power plants. This will increase the electricity demand and decrease the electricity production at the same time as the CHP units have to decrease their heat production. By 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 order to improve the possibilities of minimising the electricity export, heat storage capacity can be included in both strategies.

For a precise description of the model please consult [9].

RESULTS

First the different regulation systems have been analysed on the EnergyPLAN Model for the Eltra 2020 scenario. Figure 4 show the results in terms of surplus electricity production.

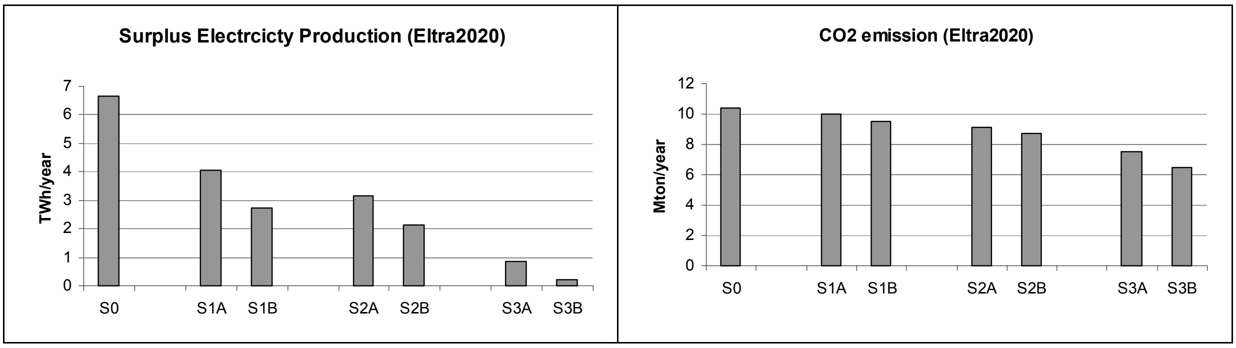

Figure 4. Illustration of abilities to balance electricity supply and demand expressed in terms of surplus electricity production in the "Eltra 2020" system (Electricity demand = 24,87 TWh, CHP District heating demand = 21,21 TWh)

Activating the CHP units in the balancing task (System 1) cut surplus production by nearly half. The CO_2 emission is decreased along with the reduction in surplus production. Meanwhile the CO_2 emission is also increased due to the loss in fuel efficiency. Consequently the net reduction is very small.

Adding heat pumps to the system (System 2) makes it possible to reduce surplus production further, and at the same time reduce CO_2 emission even more. In systems 1 and 2 it can be seen that the inclusion of small- and medium scale CHP units in the task of securing grid stability (System 1B and 2B) has a quite an influence on the system.

Including electricity for transportation (System 3) nearly makes it possible to avoid surplus production and reduce CO_2 emission further.

The results in figure 4 illustrate the ability of the different regulation systems to balance supply and demand in the given scenario Eltra 2020 in which the wind power production is 12,16 TWh compared to an electricity demand of 24,87 TWh, i.e. nearly 50 per cent of the demand. Meanwhile the ability of the regulation systems is subject to the wind power percentage. To analyse such correlation a modelling of a number of different wind power inputs has been calculated. The results of the three regulation systems are shown in figure 5 and 6 respectively with (system B) and without (System A) being included in the task of grid stabilisation. In Both diagrams the results are compared with the reference (System 0).

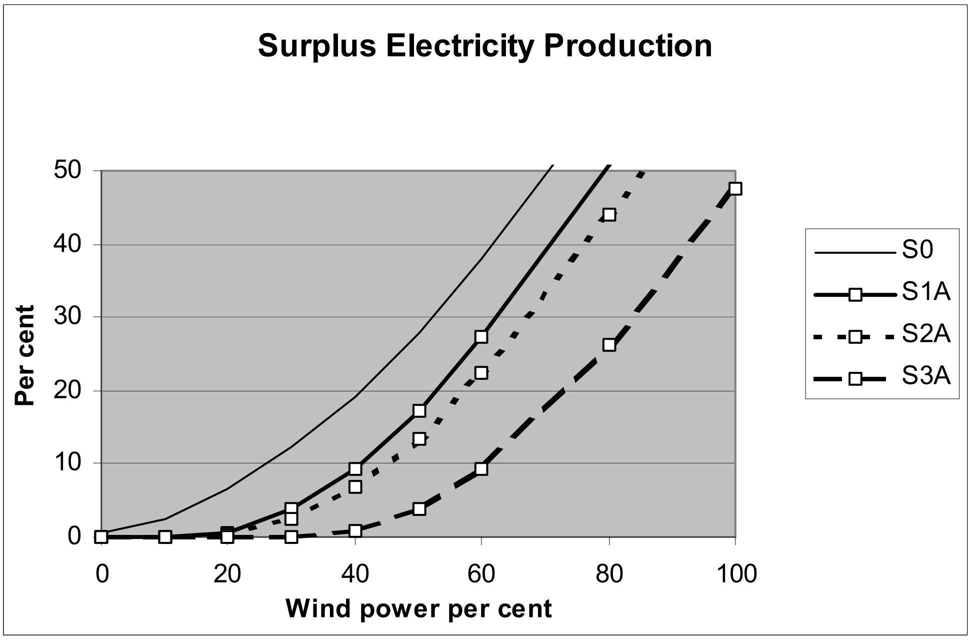

Figure 5: The ability to reduce surplus production
when systems are not included in the grid stabilisation task.

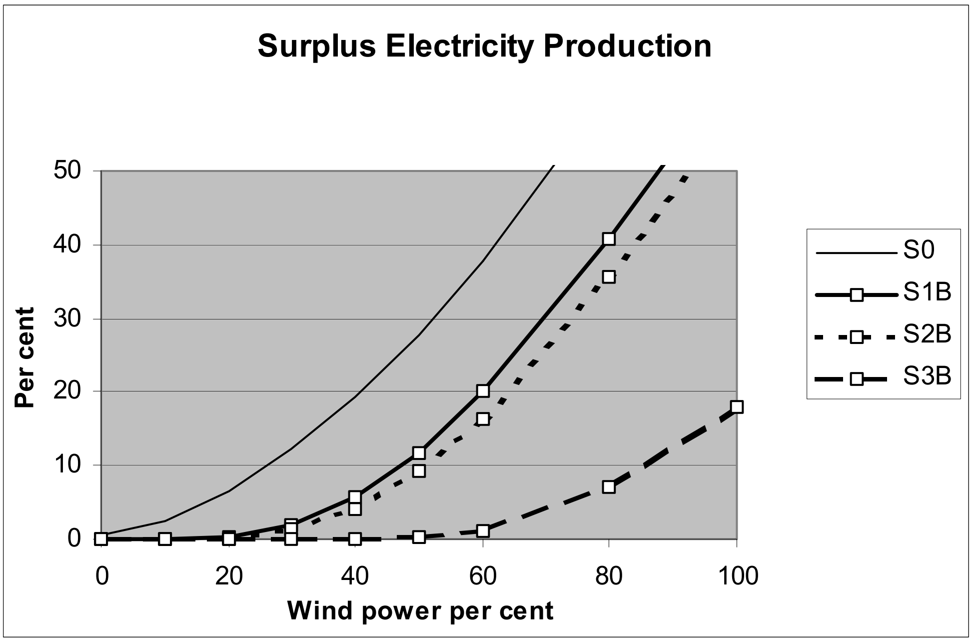

Figure 6: The ability to reduce surplus production
when systems are included in the grid stabilisation task.

In figures 5 and 6 the ability is illustrated in terms of surplus electricity production as a function of the wind power input. Both values are given as percentage of the electricity demand. The diagram should be read in the following way: for a given wind input of 40 per cent the SO-curve representing the reference results in a surplus production of 20 per cent. Consequently only half of the wind power input can be utilised directly in the system. For the same input the S3-curve (both S3A and S3B) results in a surplus production of approximately 0. Consequently all the wind input can be utilised directly if such a regulation system is implemented.

In the Eltra reference scenario the wind power input in year 2000 was approximately 20 per cent. Figures 5 and 6 illustrate how such a wind power input creates a small surplus production, which was actually the case. Meanwhile the surplus production problem can easily be avoided by activating the small and medium CHP units in the balancing task. And this step is under implementation in Denmark.

In the reference scenario the wind power input is planned to increase to 25 per cent in year 2005 and 35 per cent in year 2010. Consequently, further steps such as including the CHP units in the grid stabilisation task and/or investing in heat pumps should be considered.

In year 2020 the wind power in the reference scenario increases to almost 50 per cent. Consequently, inclusion of electricity for transportation should be considered, if all surplus production should be avoided.

CONCLUSION

Until now, the task of balancing supply and demand and the task of securing frequency and voltage on the grid has been left solely to large production units. Meanwhile, the implementation of cleaner technologies such as renewable energy sources (RES); combined heat power production (CHP) and energy conservation is necessary for future sustainable energy systems. Consequently such distributed production units sooner or later need to contribute to the task of securing a balance between electricity production and consumers demand.

This paper has presented an analysis of three potential future technical regulation systems in which wind power and small and medium scale CHP units are involved in the balancing and grid stabilising task. The results indicate that such systems can improve the ability to integrate renewable energy into to the energy systems.

In the present system in western Denmark with a high degree of CHP the integration of 20 per cent wind power already results in surplus production problems, and with a 50 per cent wind power input the surplus production is likely to raise to approximately 30 per cent. While in the three potential future regulation systems the surplus production can be minimised to between 0 and 15 per cent depending of the regulation system. And surplus production can nearly be avoided as far as a wind input of up to 60 per cent, if parts of transportation are electrified.

ACKNOWLEDGEMENT

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