Mix of power system flexibility means providing 50 % wind power penetration in the Danish power system in 2030

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Mix of power system flexibility means providing 50 % wind power penetration in the Danish power system in 2030

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***Abstract*--Time series simulations of an example of a realistic modified energy system in Denmark 2030, assuming no internal power transmission bottlenecks, indicates that it is both technical possible and economic feasible to maintain the energy balance on hourly basis, even with a wind power penetration of 50+ %. The analysis was made in 2006 as part of the study Energy Plan 2030 under the Danish Society of Engineers, IDA , using the EnergyPLAN model, developed by Aalborg University, Denmark . The paper presents the actual mix of means used in the simulation, best meeting the objectives defined for the study – high security of energy supply, substantial CO_2 emission reduction and increased Danish technology business.**

***Index Terms*—CHP; CO2; energy plan; energyPLAN; energy storage; energy system; flexible demand; flexibility means; power system; wind power.**

I. Introduction

The main challenge by large-scale integration of little controllable and little predictable energy sources – like wind power – is the necessary redesign of the remaining part of the power system.

Traditionally, for power systems, the power demands are relatively predictable and the power generations are fully controllable – making it relative easy to balance the power at any time at any point within the power system. Wind power, however, is less predictable and less controllable than traditional power generation – requiring extended flexibility in the power system to properly integrate large amount of wind power. The higher wind power penetration, the more flexibility is needed, and the more will the wind power influence the optimal power system design.

The aim for the Danish power system is to be able to handle up to 50 % wind power penetration. This requires a rethinking and a redesign of the entire power system and its operation. But, it seems to be both technical possible and economic feasible, which is supported by several studies. The present paper presents one of these studies.

The developments of the penetration levels of the wind power have went extremely fast – in Denmark from 1 % to 20 % in less than 20 years. The general power system development, required to integrate (not just adapt) and fully benefit from large amount of wind power, has not been able to follow this trend. The lifetime of the power system components is typically longer than 20 years, and a transition of the fundamental power system design takes decades.

The various local power system impact challenges at the grid connection point of the wind farm may be met by known technical means – like control of the active power, control of the reactive power, connecting the wind power to a substation with sufficient short circuit and power transmission capacities, designing the wind turbines to provide fault-ride-through etc.

In general, in order to proper integrate wind power, the power system needs flexibility. Several of the technical means to provide this flexibility are not very well known, and have indeed not been tested in real and complex power systems. The necessary power system flexibility required for large-scale wind power integration should not be provided by any single technical mean, but should rely on a coordinated combination of all available means. The means include: increased generation flexibility, energy buffering (storage), flexible demand, extended power exchange (import / export), exchange with other (energy) sectors, and not least modified control.

In the present Danish power system the level of wind power penetration is 20 %. The Danish government has announced an ambition to achieve a wind power penetration of 50 % in 2025 [1]. In addition, Denmark is committed by the Kyoto Protocol to reduce its CO_2 emission

Already at the present level of wind power penetration, the Danish power system face problems with insufficient flexibility, resulting in periods with surplus power generation capacity, zero market power prices and power transmission constrains. It is still only in few and short periods during the year and involving insignificant amount of energy. However, with the expected wind power development in the Danish power system, efficient integration of the wind power requires a more flexible power system. The lack of flexibility is a result of a power system designed and optimized to yesterday's power system, based on few central thermal power plants and little demand flexibility.

All available flexibility means should be utilized, and new should be developed and introduced.

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II. The IDA Energy Plan 2030

The IDA Energy Plan 2030 was developed in 2006 (under the IDA Energy Year 2006 project) through a participatory process involving 1600 experts in 40 workshops.

The defined goals for the energy system in 2030 was

- to maintain the security of supply,
- to half the CO_2 emission, and
- to double the national energy business

relative to year 2004.

A reference scenario for year 2030 (Ref 2030) was developed, based on the base scenario in the official Danish Government Energy Strategy 2025 [1].

The work was organised under the 7 themes:

1. buildings,
2. industry,
3. oil & gas,
4. transport,
5. fuel cells, batteries and biofuels,
6. wind, sun and waves,
7. energy systems.

For each of the themes, the technologies realistic contributions to the defined goals and their costs and benefits were estimated. And all the individual elements were combined in a simulation model for the Danish energy system, simulating one year in one hour time steps, using the simulation tool EnergyPLAN[1], developed at Aalborg University, Denmark[2]. The simulation was used to ensure that all individual measures would work together, to optimise the actual composition of measures and to quantify the impacts, costs and benefits. All result are relative to the 'business-as-usual' reference scenario.

To test the robustness of the recommended measures, the results sensitivities to variations in investment costs, international oil prices and interest rates was tested. And to test the long term robustness of the directions in the recommendations, a 2050 scenario with 100 % renewable energy was developed and tested.

The optimization process ended up with an energy system for Denmark in 2030, providing the same energy services as for the reference scenario with less total energy consumption, due to energy efficiencies, less use of fossil fuels and less CO_2 emission, due to more renewable energy sources.

The main results from the simulation of the optimised Danish energy system 2030 are show in the figures below. The total annual energy consumption and the distribution between the sectors are in Figure 1 compared between the reference scenario (Ref 2030) and the IDA proposal (IDA 2030). The annual amount and distribution of the primary energy resources needed to fulfil the energy services are in Figure 2 compared between present (2004), the reference scenario (Ref 2030) and the IDA 2030 proposal (IDA 2030). For the reference scenario the total annual energy supply is expected to increase from the present 860 PJ to 980 PJ in 2030 with 190 PJ from renewable energy sources, while the total energy supply for the IDA 2030 proposal is expected to decrease to 590 PJ with 280 PJ (nearly 50 %) from renewable energy sources. In the reference scenario, the annual power consumption for Denmark is estimated at 49 TWh (175 PJ), while in the IDA proposal this has been reduced to 35 TWh (125 PJ) due to higher energy efficiencies. The decreasing in the total energy consumption, even with an expected increase in energy services, is obtained by substantial investments in energy efficiencies.

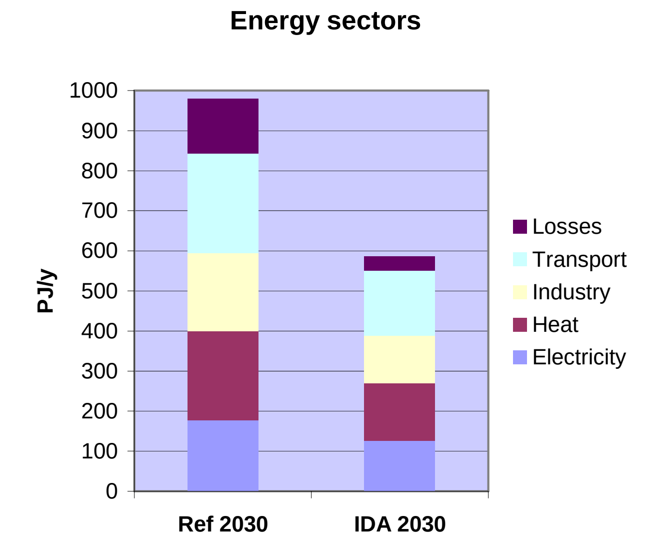

Figure 1: The estimated distribution between the sectors in 2030 for the reference scenario (Ref 2030) and the IDA proposal (IDA 2030).

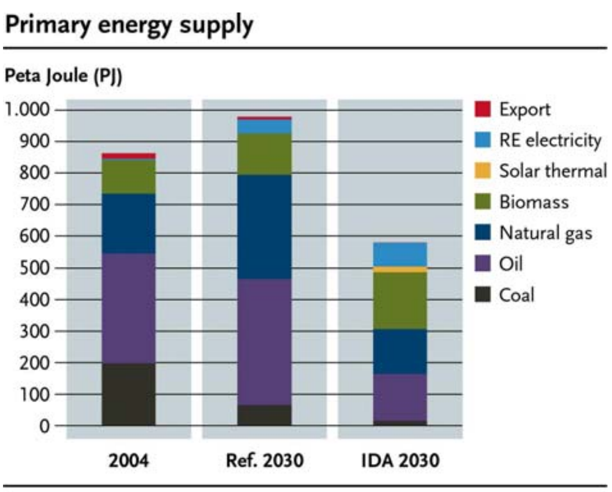

Figure 2: Comparison between the present (2004), the reference scenario (Ref 2030) and the IDA proposal (IDA 2030) of the annual primary energy supply needed to fulfil the present / expected Danish energy services. [2]

The combined investments in energy efficiencies and renewable energies results in a substantial decrease in the fossil fuel consumptions – from 800 PJ annually in the reference scenario to 300 PJ in the IDA proposal – resulting in a corresponding reduction in the annual CO_2 emission from 53 mio ton to 20 mio ton – more than 60 % reduction (Figure 3)!

[1] www.energyplan.eu
[2] www.aau.dk

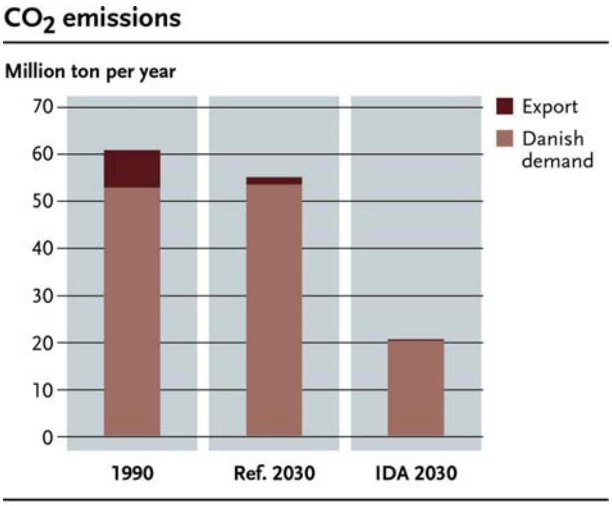

Figure 3: Comparison of the annual CO_2 emissions. [2]

The business potential is not estimated for the reference scenario in [1], but for the IDA proposal it is expected to grow from the present annual DKK 32 billion (2004) to DKK 163 billion in 2030 – corresponding to 500 % increase (Figure 4).

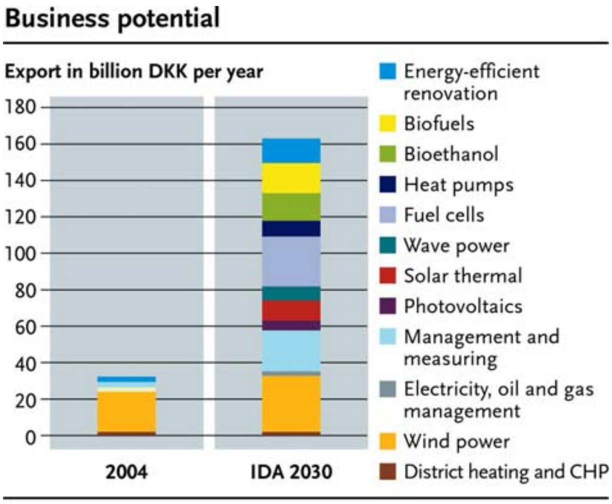

Figure 4: Estimated business potentials for the various energy technologies – present (2004) and for the IDA proposal. [2]

The estimated annual economic costs are compared for the reference scenario and the IDA proposal in Figure 5. Due to the reduced fuel costs, the total annual costs are expected to be reduced from DKK 83 billion to DKK 67 billion, and the distribution of costs are shifted from mainly fuel costs (75 %) to almost 50 % being investment costs. The oil price has been set to 70 USD per barrel, the power price to 350 DKK/MWh, and the CO2 cost to 150 DKK/ton. An investment rate of 3 % has been used.

The IDA proposal fulfils the defined goals through a combination of comprehensive investments in energy efficiencies and shifts from fossil fuels to a broad collection of renewable energy sources – with wind covering more than 50 % of the power consumption.

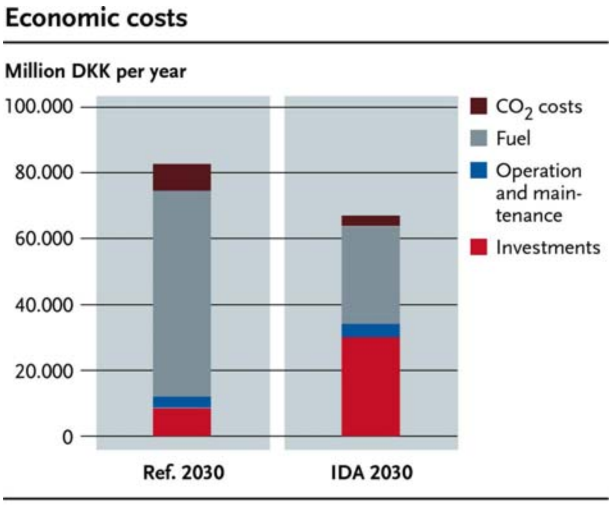

Figure 5: The estimated annual economic costs for the reference scenario and the IDA proposal. [2]

III. Power system flexibility means

In general, the optimal solution for large-scale integration of wind power is based on an optimised combination of all available flexibility means in combination with increased predictability, increased controllability and reduced fluctuation of the wind power generation.

A number of technical means may contribute to the necessary power system flexibility, including:

- flexible generation
- flexible load
- extended power exchange
- extended exchange between energy sectors
- storage of electricity

A. Flexible generation

The various power generation technologies provide different degree of flexibility in their power generation – from nuclear power plant as the one extreme, providing little flexibility, to hydro power as the other extreme, providing high degree of flexibility in their generation. Most thermal power plants have long start-up times, relatively high required minimum load levels and slow regulation of the generation level. Hydro power can be started up immediately (no start-up time), can operate at low load and can regulate the generation level very fast, both up and down.

B. Flexible load

In most power systems, most of the power demand is not flexible and is only little price sensitive, and this only on a very long time scale (years) – mainly because the consumption is charges at fixed price, independent of when and where in the system. However, several loads may be regulated with no or minor inconvenience for the energy service – e.g. shifted in time, adjusted in level or partly replaced. Examples are heating, cooling, pumping and charging that typically may be shifted several hours in time with no inconvenience for the user; lighting level (e.g. street lighting) may be adjusted for a period with minor inconvenience; and electrical heating may be replaced dynamically by fossil fuel heating (e.g. in combined CHP and heat-pumping plants).

C. Power exchange

Extended power transmission capacity will contribute to the extended flexibility by allowing extended power exchange between regions. The correlation between simultaneous fluctuating wind power generations at different locations decreases in general with the distance between the locations (Gregor figure). The aggregated wind power generation from several wind turbines / wind farms distributed over a large area, interconnected by adequately power transmission lines, will therefore show less relative fluctuation than from each individual wind turbine.

D. Exchange between energy sectors

One example is the exchange between the power sector and the transport sector. 'Surplus' electricity may via electrolysis be converted to hydrogen, which again may be converted to an appropriate (liquid) fuel for the transport sector. And 'surplus' hydrogen may via fuel cells be converted back to electricity (and heat).

E. Energy buffering

One example is the combined heat and power generation – relevant in regions with heat needs most of the year, as in most northern Europe. All energy conversions technologies generating power will also generate heat, which may be utilised, typically for heating of buildings. The ratio between the heat and the power generation may be controlled within limited boundaries – at least 40-50 % of the energy will always end as heat.

The actual optimal combination of the various flexibility means will depend on actual conditions – including the actual mix of active units in the power system, the actual market structure and (international) prices, the actual investment and operation costs, the actual amount of flexibility needed, and the value of the flexibility.

IV. Wind power plant characteristics

Wind power generation may be given more power plant characteristics – including increased predictability, increased controllability and reduced fluctuation of the wind power generation.

A. Predictability

With multi information input from weather forecast and distributed on-line wind measurements, the short-term predictability of the actual wind resources several hours ahead becomes still better. Worst cases are at large and rapid changes of the wind where the main uncertainty is on when the change will happen rather than the level. The effect may be reduced by limiting the up-regulating slope and by starting the down-regulation in advance.

B. Controllability

Controlling the power output from the wind power plant a little below the potential available wind power from the wind farm provides the ability to control the power output both up and down or smoothening out the fast fluctuations, if needed by the power system.

C. Fluctuations

The fluctuations may be smoothened by aggregating the generation from several distributed wind turbines, by absorbing the fluctuations in local buffer storage, and by operating the wind turbines at output levels below the potential levels (at the cost of loss of potential production).

V. Actual means

A. Electrical vehicles

In the IDA proposal, 20 % of the Danish person transport vehicles (400 000) are assumed to be electrical vehicles in 2030. The electrical vehicles are expected to be 80 % more expensive than the corresponding ICE vehicles, but are expected to be more energy efficient – from 20 % for the ICE vehicles (corresponding to 18 km/l gasoline) to 85 % for the electrical vehicles (ex grid).

On annual basis, the fleet of electrical vehicles requires 1 TWh (3.5 PJ) charging energy – or in average 100 MW. The electrical vehicles assumes in average to be connected to the grid in 50 % of the time. To make the simulation simple, the charging power assumes to be fully flexible when the vehicles are connected to the grid.

B. Combined heat & power generation

In Denmark, most of the buildings space heating is based on utilising the heat from combined power & heat generation (CHP). Most of the CHP technologies provide some flexibility in the ratio between power and heat generation – typically from 50/50 % to 0/100 %. The heating systems – in specific the district heating systems – act as short-term energy buffers, providing the flexibility to shift the heat (and power) generation few hours in time. In the IDA proposal, 20 % of the CHP is in 2030 based on natural gas fueled fuel cell technologies (both for district heating and for household micro CHP) with high power efficiency (50 %) and extended flexibility.

Fuel cells used for combined heat & power generation are very flexible and fast in operation with high efficiency over the full range.

When using electricity for (district) heating, the energy efficiency is increased (to 300 %) by the use of electrical heat pumps, increasing the ambient temperature (air or ground) to 50-60 °C.

C. Wind power integration

In the IDA 2030 proposal 6000 MW wind power is assumed in Denmark 2030 (50 % increase relative to 2004), producing annual 19 TWh, corresponding to 55-60 % of the total 35 TWh power demand.

Introducing this amount of wind power without introducing new flexibility means in the power system results in substantial amount of surplus power (11.9 TWh) of no value – flexibility level O in the table below.

Introducing flexible ratio between heat and power generation in the decentralized CHP plants by market response, these plants will produce less power at a lower total efficiency. This reduce the amount of surplus power to 3.6 TWh, but with an increase of the total energy from 581 to 604 PJ – flexibility level I in the table.

Introducing electrical heat pumps at the decentralized CHP plants to produce the needed heat reduce the total energy to 578 PJ and at the same time reduce the surplus power to 2.6 TWh – flexibility level II in the table.

At flexibility level III in the table, the regulating power original provided by operating large and slow centralized thermal power plants at a minimum generation level is substituted by the much more flexible and faster fuel cells, reducing the surplus power to 1.7 TWh.

Finally, at flexibility level IV in the table, 10 % of the load is assumed flexible, including the fleet of electrical vehicles. The surplus power is almost eliminated (reduced to 0.6 TWh or less than 2 %)

Flexibility level	O	I	II	III	IV	
Total energy	581	604	578	580	581	PJ
Surplus power	11.9	3.6	2.6	1.7	0.6	TWh

VI. Conclusion

The detailed simulation of the expected Danish energy system in 2030, based on qualified guesses by more than 1500 experts on technical performance and economic cost as input to the simulation tool EnergyPLAN, indicates that it is both technical possible and economic feasible to introduce more than 50 % wind power into the power system and reduce the CO_2 emission by more than 60 % relative to a business-as-usual scenario. The amount of the society's required energy services has not been changed. Efficient integration of more than 50 % wind power penetration in the power system has been achieved through the introduction of a number of flexibility means – including flexible CHP production, flexible electrical heat pumps, flexible fuel cell CHP and flexible load demand. The substantial reduction in CO_2 emission is achieved through a combination of increased energy efficiency and shift from fossil fuels to renewable energy resources. The economic feasibility is achieved through a combination of a shift from annual fuel costs to investments in energy efficient technologies and substantial expected increased business potential in the energy sector. The robustness of the results has been tested by sensitivity analysis on investment costs, oil prices and interest rate.

VII. References

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VIII. Biography

Per Nørgaard, born in Denmark 1951. He graduated as MSc in Electrical Engineering from the Technical University of Denmark, DTU, 1976. His employment experience included the Roskilde University and Risø National Laboratory American Telephone Company, Budapest, the Edison Machine Works, Westinghouse Electric Company, and Nikola Tesla Laboratories. His special fields of interest included integration of wind power.