Grid requirements with scattered load balancing and an open electricity market

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Abstract
Denmark is in a situation with many scattered sources of electricity, that are not controlled by the central load dispatch. At the same time, Denmark is being used as an electricity transit corridor between Norway/Sweden and Germany. Through energy systems analyses and load-flow analyses, it is determined that if scattered load balancing is introduced, electricity transit is enabled to a higher degree than if central load balancing is maintained. This is the case with an intact transmission system as well as with a system with transmission lines down.

Introduction

One of the focal points of Danish energy policy is climate change mitigation. As one of the first countries in the world, Danish established a national carbon dioxide emission reduction target in 1990 [1] following the recommendations of the 1988 Toronto Conference on the Changing Atmosphere. Denmark was at that point and is still one of the nations with the highest level of carbon dioxide emissions per capita. Through various measures, however, a decline in the level was brought about. This is noticeable considering the almost continuous increase up to 1990.

Various measures were employed to realize the decrease. Increased utilization of renewable energy sources, increased usage of cogeneration of heat and power (CHP)-based district heating, fuel substitution from coal to natural gas, and end-use energy conservation were all elements adding to the decrease.

As a consequence, wind power thereby evolved from being an aberration in Danish electricity supply to being a generation technology with a noticeable production share reaching 12.6% in year 2000 (see figure 1). Denmark is split up into two independent electricity system, and in the largest - the Jutland-Funen area, the share even reached 16.4% in 2001 [2]. Wind can be expected to increase its share even further as development is moving off-shore, where wind resources are even better than on land. Additionally, six out of seven years since 1994 have had wind energy contents below average, so a return to more normal wind conditions may boost production considerably.

The level of CHP also increased from about 40% of total electricity generation in Denmark before the first oil crisis to more than 120% of total electricity generation adjusted for import and export in 1996 as shown in figure 1. The abrupt changes from year to year resulting in the jagged shape of the curve is due to variations in temperatures from year to year and thus in heat demands and consequently electricity generation on CHP plants. 1996 was for instance a cold year whereas 2000 was a warm year.

CHP has thus reached a high generating share in Denmark and presently, the development has slowed down considerably. If however new technologies such as micro-sized CHP units for individual dwellings become economically attractive, a further expansion could be foreseen.

Power plants may be both central and local. Central power plants are power plants where the power generation any given moment is controlled from the central load dispatch. In Denmark this is typically large condensation or CHP plants. Local power plants, on the other hand, are plants where power generation only is controlled locally and thus not by the central load dispatch. In Denmark this is typically small-scale CHP plants.

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CHP thus takes place at large central plants as well as smaller local plants. In the course of the development of CHP, the threshold size of towns with sizes economically favourable for CHP in combination with district heating has dropped. The first towns with CHP based district heating were the largest cities in Denmark - the cities with central power plants. Increasingly smaller towns were then equipped with CHP based district heating as the threshold size dropped. The smaller plants, however, are for various reasons local i.e. not centrally load controlled. The development has consequently been towards increasing shares of local CHP plants as indicated in figure 1.

With increasing shares of wind power generation and local plants, the production share of central plants is thus falling. From a production share of about 99% in the 1970s and the first half of the 1980s, the share reached a low in 2000 at about 63%. In spite of a certain geographic equalization of weather, especially wind power generation may fluctuate considerably [3]. Also local CHP generation, however, may fluctuate in a manner counterproductive to load balancing. Central load balancing where only the very limited number of central plants are actively controlled, is thus made increasingly difficult and the transmission and distribution grids are subjected to use not anticipated when constructed.

At the same time, there is an increased need for transmission capacity due to market reforms and the use of Denmark as a transit corridor between on one side Germany and on the other side Sweden and Norway. Depending on precipitation and water levels in hydroelectric dams on the Scandinavian peninsula, electricity prices may vary considerably thereby resulting in economic incentives for either importing electricity or for exporting electricity. In these situations, Denmark may pose an undesirable bottleneck. Rational utilization of the interplay between the Scandinavian hydro electricity systems and the thermal power plants of Northern Europe is one of the options for increasing the overall efficiency of the energy systems and is thus of some importance.

Previous analyses have demonstrated that the need for transmission grid capacity may be lowered in which case expansions may be avoided. Larger shares may thus possibly be allocated for electricity trade through

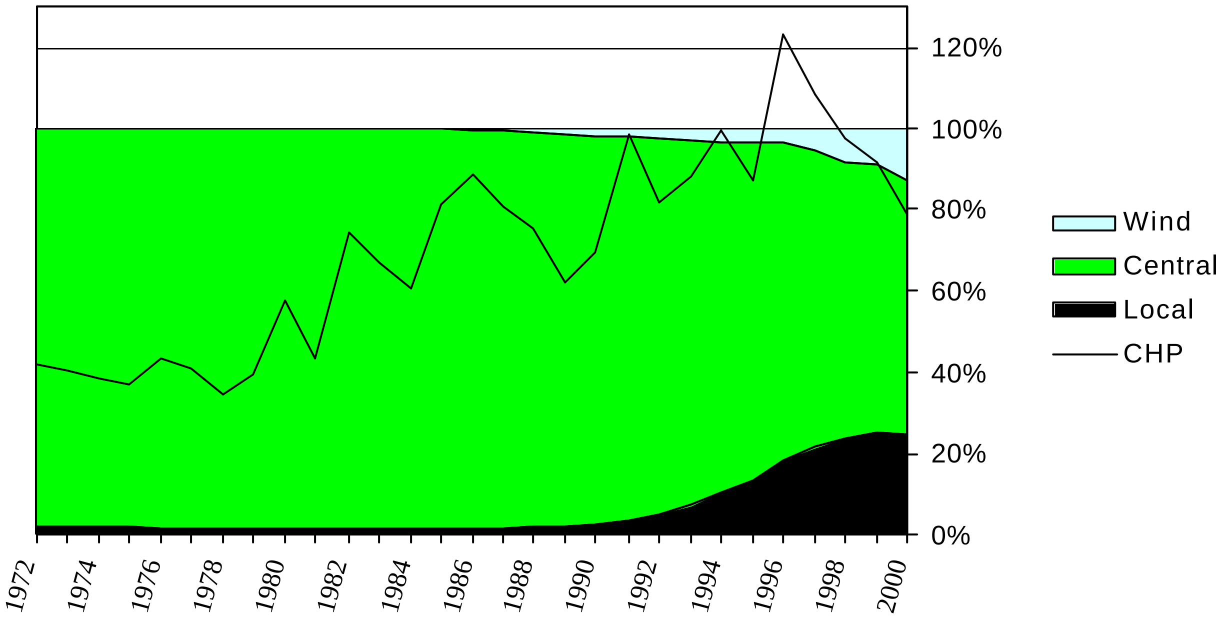

Figure 1: *Development in shares of central, local, wind and CHP(both central and local) power generation of total Danish power generation. It should be noted, that import and export are added and deducted to/from electricity generation on condensation plants thus enabling a production share above 100%. Data between 1972 and 1975 are interpolated. Based on data from [4]*

Denmark. The transmission requirements are lowered by maintaining load balance with the active help of the small scattered local plants and the use of e.g. scattered heat pumps and electrolytic converters [3, 5, 6]. If local plants are actively controlled centrally, of course, they become central. In this article, however, the term "scattered balancing" refers to the situation where the operation of small and geographically scattered plants is also controlled centrally. This is thus a distinction from central load balancing, where only few large plants are controlled directly.

Left unaddressed, growing amounts of uncontrolled or uncontrollable electricity generation would generate a need for transmission to other countries which may not be accommodated - and which may not be economically favourable considering the poor bargaining position of the seller. Rather than e.g. shutting wind turbines down, scattered load balancing demonstrates a more energy efficient approach. Direct control of the production on the scattered hitherto local CHP plants is one of the measures, shift from CHP heat production to heat production on heat pumps is another and electricity use for vehicles - either through battery chargers or electrolytic converters - is a third.

Scope of this article

The previous analyses referred to, however, have all assumed intact transmission grids. Transmission lines or other components may be out of order due to maintenance or unforeseeable events causing failures. Maintenance may be carried out at times of the year with low loads whereas unforeseeable failures may occur at the annual peak load. The grid must sustain such failures.

Grid expansion in the Jutland-Funen area of Denmark has traditionally been planned according to criteria C (see table 1). It has furthermore been planned deterministically i.e. through the modelling of the grid in few determining (worst) cases.

Criteria A is increasingly being considered [8] as the free and unhindered use of different production plants is important to the functioning of the electricity market. As the transmission and dispatch company Eltra states

> *"One of the main perspectives for the expansion of the transmission grid er are the frames the market render"* [9]

The question is however, whether the transmission system should be designed in a way that enables any use - that is should it be strong enough to assist any imaginable combination of production on various plants or should its design be limited to fewer production strategies. Apart from being costly, grid expansion may also affect the scenery and particularly in Denmark, there is a certain opposition against grid expansion. The domestic market may however be fashioned in a way that furthers scattered load balancing and thus lowers requirements of the transmission grid. Particularly as proper use of the energy system furthers Denmark's

Criteria	Consumption load	Description of Criteria
A	-	Free use of the production system and international connections even lacking one line or one transformer
C1	#90% of yearly maximum	Supply must be secure regardless of following faults: Two production units and either a transformer or a line down or One production unit and two lines down
C2	#100% of yearly maximum	Supply must be secure regardless of following faults: One production unit down and either a line or a transformer down

Table 1: *Criteria used for grid-expansion. Source [7]*

energy policy ambitions in regard to energy efficiency and climate change mitigation.

The scope of this article is hence to investigate how much electricity may be transmitted through Denmark with scattered and central load balancing respectively and with a starting point in grid-expansion criteria C2. Only transmission between Norway and Germany is considered in this article.

Modelling the energy system

The point of departure for the analyses are energy systems analyses made in [10,11] where scattered balancing is applied to maximize the utility of especially wind power generation and CHP plants. The analyses are carried out in a future situation with even more wind and CHP than what exists presently. They are furthermore carried out for the Jutland-Funen area only. General determinants of the energy system are listed in table 2.

	2020 Central balancing	2020 Scattered balancing
Wind	2500 MW on-shore 1445 MW off-shore	2500 MW on-shore 1445 MW off-shore
CHP	2600 MW	2600 MW
HP	0 MW	650 MW
Condensation	1900 MW	1900 MW
Consumption.	24.87 TWh/year	24.87 TWh/year

Table 2: *General determinants of the energy system analysed.*

The determinants originate from work carried out by a working group under the Danish Energy Agency established to consider this general problem area.

The main difference between the two situations - apart from various technical differences attributed to load balancing and thus not shown in table 2 - is the considerable capacity of heat pumps installed in the latter case. Heat pumps are presently installed at e.g. individual dwellings but these heat pumps are assumed installed at district heating plants - and they are assumed centrally controllable in contrast to the presently existing individual heat pumps

The energy system is modelled with the EnergyPlan model [10,11] and outputs include hourly values (MWh/h) of production and consumption on the various relevant types of equipment. Sets of productions and consumptions values are selected deterministically among these for further load-flow analyses.

Previous analyses have indicated that the transmission grid is put under particular strain with central load-balancing if it is cold - with a resulting high electricity production on CHP plants - windy and late at night with low electricity consumption. In such situations, there is a large scattered electricity production that is not consumed locally and which must be picked up and transmitted elsewhere [4]. This situation is analysed here even though it is in contrast to criterion C, which assumes maximum consumption. However, due to the development hitherto, transmission loads are not necessarily peaking when consumption is peaking.

Load situation	2020 Reference		2020 Scattered balancing	
High wind	Heat pump	0 MW	Heat pump	650 MW
Low electricity consumption	Transport	0 MW	Transport	405 MW
January, 1 a.m	Consumption	2375 MW	Consumption	2318 MW
	Off-shore	1403 MW	Off-shore	1403 MW
	On-shore	2239 MW	On-shore	2239 MW
	Power Plant	0 MW	Power Plant	0 MW
	CHP	2600 MW	CHP	200 MW

Table 3: *Power generation and consumption in the scenarios analysed .*

For the load-flow analyses, a January night case is thus identified, as detailed in table 3. These productions and consumptions are distributed geographically using the PlanToGrid programme module [3]. PlanToGrid uses series of index figures to associate productions and consumptions with the nodes of the transmission grid - here limited to 150 kV and 400 kV transformer stations.

Modelling load-flows

The resulting matrices of active and reactive power consumptions and productions in all nodes are fed to the energyProGrid model [12] for load-flow analyses. In addition, the energyProGrid model is fed with a description of the grid i.e. admittance, reactance, resistance and maximum currents of the individual lines as well as size and short circuits resistance and reactance of transformers from [13] (see table 4). A year 2000 description is selected for the analyses; the newest available. The resulting set of matrix equations is subsequently solved numerically rendering line currents and voltages throughout the grid. Comparison of actual with permissible line currents finally reveals over-loads

The model does not treat the transmission system pro-actively - i.e. loads are not shifted between different lines to avoid overloads. However, the system is treated analogously in the two cases, so indications of over-loads in one case and not the other may be seen as a general indication of higher loads in the one case compared to the other.

Start Node	End Node	Voltage [kV]	Distance [km]	Resistance [O]	Reactance [O]	Admittance [µS]	Max Current [A]
ALD	ÅBØ	150	14.20	0.53	3.13	76	1380
KAS	TJE	400	173.15	4.91	58.28	598	1200

Table 4: *Excerpt of the transmission grid description.*

The transmission system is as illustrated in figure 2, and it is evident there are numerous possible faults, to which the system response may be analysed. However, there are two 400 kV connections up through the Jutland peninsula of which one connects the converter station for the Norwegian sea cable to the Kassøe node in Southern Jutland, which is the connection point for most connections to Germany. This 830 MW line is thus particularly interesting in regard to the area being used as a transit corridor and faults on this line along with transit between Norway and Germany is thus analysed.

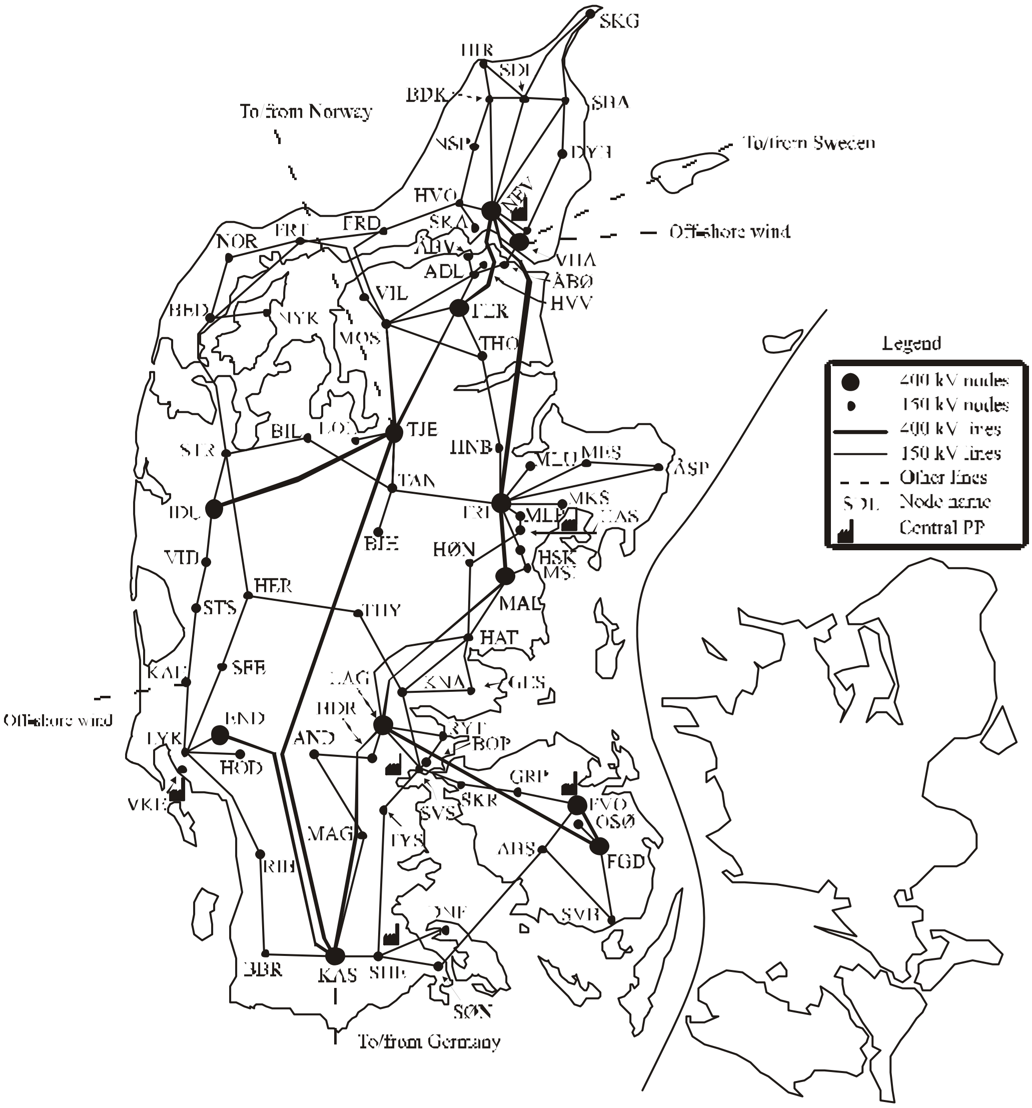

Figure 2: *Map of the transmission system modelled in this article. The islands to the East are on a separate transmission system*

Table 5 details the cases analysed as well as the results of the analyses. With central load balancing, there is no surplus capacity for transit purposes as a large Danish surplus productions needs to be transmitted elsewhere. Many lines are overloaded regardless of whether the 400 kV KAS-TJE line is down or not. In fact, in the scenario analysed, the capacity of international connections is insufficient for the domestic surplus production.

With scattered load balancing, a small number of lines overload. The KAE-LYK line is overloaded in most cases and so is the 400 kV line between NEV and VHA. NEV and KAE are entry points for large marine based wind farms and are apparently too weak. Otherwise, only few lines overload regardless of the status of the KAS-TJE line. With 250 and 500 MW from Norway to Germany, one extra line overloads in case the KAS-TJE line falls out indicating a higher resilience to faults with scattered load balancing. If transit is reversed i.e. from Germany to Norway (not shown in table 5), only the NEV-VHA line overloads even at 1000 MW.

Case		Grid response	
Line down	Transit	Central balancing	Scattered balancing
No lines down	No transit	Many overloaded lines	NEV-VHA 400 kV
KAS-TJE down	No Transit	Many overloaded lines	KAE-LYK NEV-VHA 400 kV
No lines down	250 MW Norway-Germany	Many overloaded lines	KAE-LYK NEV-VHA 400 kV
KAS-TJE down	250 MW Norway-Germany	Many overloaded lines	KAE-LYK NEV - VHA 400 kV HER-STR
No lines down	500 MW Norway-Germany	Many overloaded lines	KAE-LYK NEV-VHA 400 kV
KAS-TJE down	500 MW Norway-Germany	Many overloaded lines	KAE-LYK NEV-TRI HER-STR

Table 5: *Results of the transmission grid load-flow analyses.*

Conclusions

If scattered load balancing is introduced, the need for transmission capacity is decreased thereby allowing for higher transit between Norway and Germany. Due to the generally decreased transmission needs with scattered load balancing, the resilience of the transmission grid to faults is higher. Even in a worst case situation as the one analysed, and even with faults in the transmission system, transit may be accommodated thereby honouring the obligation to permit such. At peak load of the transmission system 500 MW may be allocated for transit from Norway to Germany with an intact transmission system. With one important line down, transit may be permitted to a lesser extent but still to a reasonable degree. The analyses also show, however, that the entry points of future off-shore based wind farms need to be strong in order to avoid overloads.

References

1. Energy 2000 - A plan of action for sustainable development. Danish Ministry of Energy, Copenhagen, 1990.

2. Eltra Magasinet April 2001

3. Østergaard, P A. Modelling the geographic distribution of scattered electricity sources. Dubrovnik Conference on Sustainable Development of Energy, Water and Environment systems. Dubrovnik, Croatia, June 2002.

4. Energy Statistics. Danish Energy Agency.

5. Østergaard, P A. Transmission grid requirements with scattered and fluctuating renewable electricity

sources. Energex 2002, Krakow, Poland, May 2002

6. Lund H, Østergaard P A. Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation. Energy 2000 25(4):299-312.

7. ELSAM. Dimensioning criteria for the 400-150 kV grid. ELSAM, January 1996 (in Danish)

8. ELTRA. Dimensioning of the transmission system in Jutland-Funen. ELTRA, December 1998 (in Danish)

9. Construction plan 2001. Eltra, Skærbæk, 2001. p. 9. (In Danish, quotation is own translation)

10. Report from the workgroup on electricity production form CHP and RES, Danish Energy Agency, Copenhagen 2001 (In Danish)

11. Attachments to report the from the workgroup on electricity production from CHP and RES, Attachment 6. Danish Energy Agency, 2001. (In Danish)

12. Andersen A N. Calculations in Windows Elnet EMD, Aalborg 1999. (In Danish)

13. Grid expansion plan 1991 - Data foundation. Elsam, Skærbæk 1991. (In Danish)