Challenges in the transformation of Danish electricity supply

Conclusions

Production capacity to be multiplied by 2050
For electricity supply, the goal towards 2050 is stated in the Danish Energy Agency's "Analysis assumptions for Energinet 2024[1] (AF24). In round numbers, four times as much electricity must be delivered in 2050 as in 2025, but since wind and solar power have a lower capacity factor than traditional controllable power plants, the installed production capacity must be increased even more. This requires correspondingly large reinforcements of electricity transmission and distribution facilities.

Limits to growth?
The expansion of infrastructure is already delayed, while the electricity market is reacting with volatile prices, which are causing investors in new wind and solar plants to hold back. The plans apparently did not foresee these effects, either on the plant side or in the electricity market.

Energinet has the competences regarding the electricity market and grid expansion. It is therefore proposed that Energinet be given a more central role in the ongoing planning.

Need to recognize barriers to expansion
Danish authorities prefer to present good news while downplaying or withholding less good news. This smokescreen helps to give the public a misleading picture of the challenges and opportunities of energy supply.

The trends in Europe's electricity markets must be included in planning
This note's analyses of data from the electricity market since 2010 show trends, which indicate increasing price volatility in the spot markets. The public data lack an assessment of whether the current trends in the electricity market are permanent or temporary.

Ban on nuclear power blocks analyses
In 1985, the Danish Parliament decided that nuclear power must not be included in the planning of the Danish electricity supply. The effect of this is that the operational synergy between nuclear power and fluctuating production has, as far as is known, never been analysed. It has become a prevailing perception that it is not possible to give nuclear power plants sufficient utilisation in a system with a large share of wind and solar energy. This note will show that this thesis is not correct. It is also not correct that gas turbines will be able to make operations as efficient as nuclear power plants.

The technical and economic robustness of the electricity supply must be mapped
Lack of flexible resources makes the Danish electricity supply vulnerable, especially during crises. It is recommended that scenario techniques be used to map the vulnerabilities and to support any decisions on new preparedness measures.

Increased flexibility can make a wind and solar-based electricity system more robust
There will be a need for more flexibility on the production side than assumed in AF24. Significant improvements can be achieved by adding more controllable production, e.g. in the form of nuclear power.

[1] Energinet is the Danish Transmission System Operator for electricity and gas

Bad news

Since August 2024, a number of news about setbacks in the green transition have reached the public:

- August 2024: "Energy Island in the North Sea is delayed by at least three years"
- December 2024: "No bids for Danish offshore wind farms"
- January 2025: "Better Energy went into reconstruction with a deficit of 1.5 billion kroner"
- January 2025: "The government puts the offshore wind turbine project Energiø Bornholm on hold"
- March 2025: "Green Hydrogen Systems goes into reconstruction". Bankruptcy June.
- June 2025: "Obton A/S can drag banks down in solar cell crisis"

Better Energy and Obton are developers of solar cell parks. Green Hydrogen is developing technology for electrolysis.

In August 2024, Energinet (Danish transmission system operator) sent an email to the Ministry of Climate, Energy and Utilities with the following message: "98 of 174 expansions of Energinet's electricity network will be delayed". The content was not shared with the public or political decision-makers. In March 2025, the story was published by a Danish online media outlet, and the minister had to apologize for the omission.

Markets for new plants are under pressure

Both Danish purchases of plant components and Danish trade in electricity take place in international markets. Barriers in these markets can prevent implementation of Danish plans, but this possibility does not appear to be included in Danish energy planning.

Construction activities are growing in several countries. This has created price increases and longer delivery times, which Energinet is also struggling with. This raises the question of whether the current plans are realistic. It is always an advantage to be able to adapt the construction program to market fluctuations, but when this is not possible, one should "read" the markets and set realistic budgets and schedules.

Drastic changes in the electricity market since 2018

In recent years, there has been a tremendous growth in the connection of solar cells. This has affected the market prices for electricity, as the production of solar energy takes place within a narrow period of time in the middle of the day. Financial difficulties for large Danish developers of solar cells indicate that the changed market prices have not been anticipated.

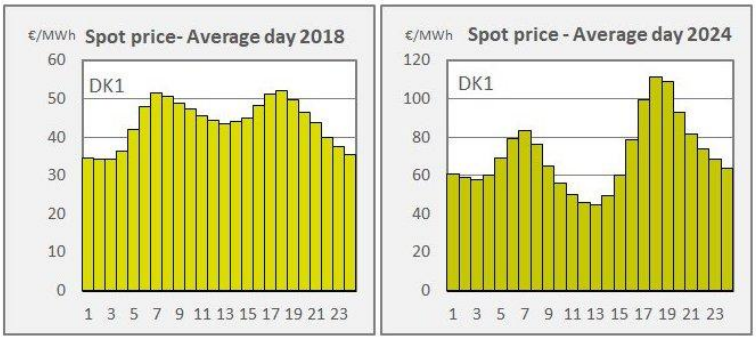

Fig. 1 - Western Denmark - Spot prices for average days in 2018 and 2024. The price levels are different due to the gas crisis in 2021/22.

To illustrate the significance of the changed prices, fig. 1 shows spot prices for average days in Western Denmark for 2018 and 2024. An average price for the entire year has been calculated for each hour of the day.

Solar cells have depressed prices in the middle of the day. This means a financial loss for sellers of solar cell production if you have budgeted with a price profile like in 2018. Due to the gas crisis in 2021/22, the general price level has changed since 2018. It has not returned to the level before the crisis.

Fig. 2 shows the same trend in Germany, even with a slightly greater spread than in Denmark.

The solar cell industry must probably prepare itself for the change to be permanent. It may be necessary to supply new solar cell systems with batteries so that deliveries can be moved to times of the day when prices are higher than in the middle of the day.

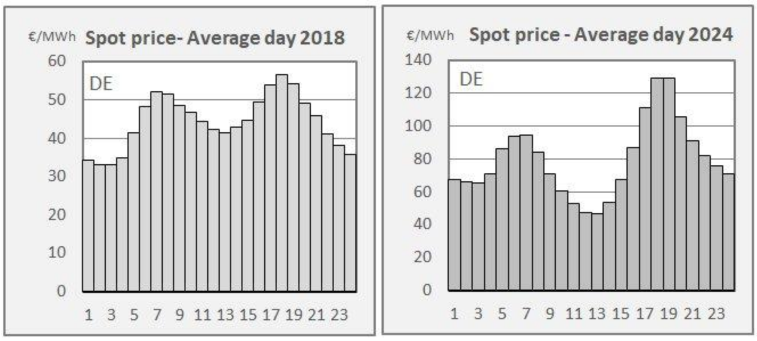

Fig. 2 - Germany - Spot prices for average days in 2028 and 2024

Worrying long-term trends in the Danish electricity market

Trade values for the main groups on the Danish electricity market have been mapped year by year since 2010. Trade values are calculated for each hour as spot price times quantity and standardized in relation to the trade value of classic electricity demand[2], which is set at 100% each year.

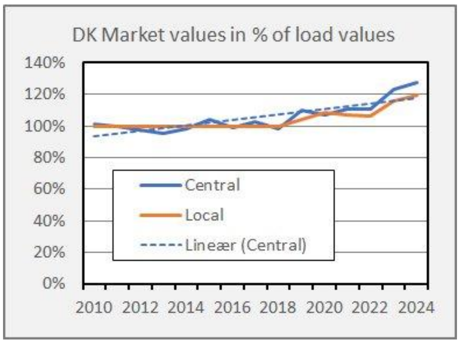

Fig. 3 - Growing market value of controllable production since 2018

For **dispatchable production** (central and decentralized), up to 2018, it was regulated up and down with consumption, which is why the trade value was close to 100% (Fig. 3). When solar energy began to affect prices, production was regulated down when the price was low. This caused the trade values to grow to around 120% in 2024.

Wind energy (onshore and offshore) occurs unevenly throughout the day, i.e. regardless of demand. The trading value has fluctuated around 80% over the years, slightly higher for offshore energy and slightly lower for onshore turbines.

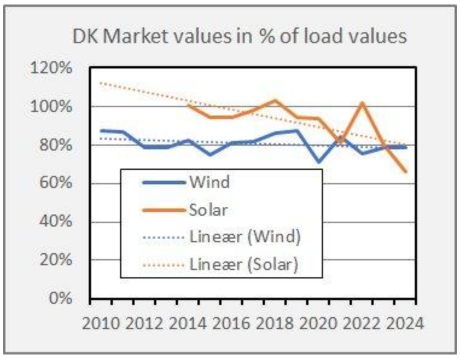

Fig. 4 - Large fluctuations in the value of solar energy

Hourly data for the production of **solar energy** is only available from 2014. The trading value was around 100% in the first years, but began **a sharp decline** as spot prices fell in the middle of the day. The increase in 2022 may be due to lower electricity consumption due

[2] Classic electricity demand: AF24 distinguishes between classic electricity consumption and new consumption types, including individual heat pumps, large heat pumps, electric boilers, data centers, Power-to-X, CO_2 capture and transport.

to Corona and the gas crisis. In 2024, the value reached 65.9%. In Germany, the trading value for solar energy in the same year was 57.9%.

For the trade value of **exchanges with neighboring countries**, the trends over the 15 years are very clear. The price of importing electricity has increased from under 100% to around 120%, while the income from exports has decreased to around 60%. This is happening in step with the winding down of controllable production in Denmark.

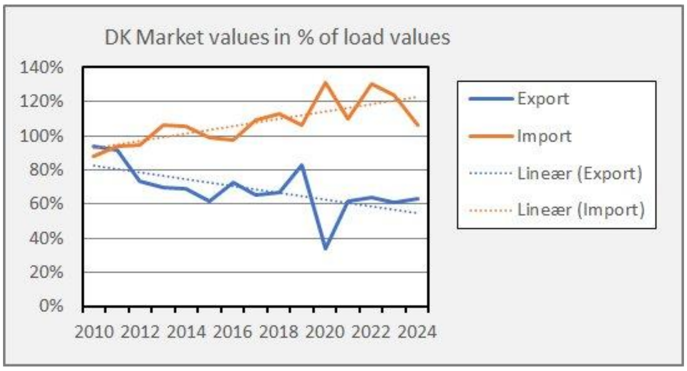

Fig. 5 - The value of exports is only half the price of imports

It is not a law of nature that these trends can be extrapolated into the future, but there is no sign that the fundamental causes are going away. Therefore, Denmark should at least prepare for it to become more expensive to import and for surplus production to become worthless. More flexibility in the Danish electricity system could reduce shortages and overflows.

Barriers and problems must be recognized and understood

The original ideas about a growing share of wind and solar energy were based on the idea that the lost flexibility in production could be compensated for by flexibility on the demand side, driven by price signals. There has been enough time to develop this flexibility, but very little has happened.

It has always been important to maintain an appropriate balance between demand, production capacity and transmission. Imbalances in this balance mean either insufficient supply or a waste of money. The forced expansion increases the risk of such imbalances.

Energy researchers have demonstrated with advanced simulation models that the green transition is technically possible all the way to a climate-neutral Denmark in 2045. However, it is already clear in 2025 that it is not going according to plan. The expansion has encountered barriers that are not represented in the simulation models.

A significant part of the reason is to be found in a pressured labor market and in congestion among suppliers of plant components. Another part is uncertainty among investors due to the high pace of expansion. Producers are waiting for demand, and large consumers are uncertain whether there will be sufficient cheap production when they are ready to go into operation.

The politically determined targets are not up for discussion, but it cannot be ruled out that better paths to the national climate targets can be found. This requires recognition of the barriers, optimization of the plans and understanding with political decision-makers.

A vulnerable electricity supply

The objectives for Denmark's electricity supply are primarily the achievement of climate goals and security of supply. The latter is assessed based on the calculations made in the European Network of System Operators, ENTSO-E, i.e. with normal international interconnection.

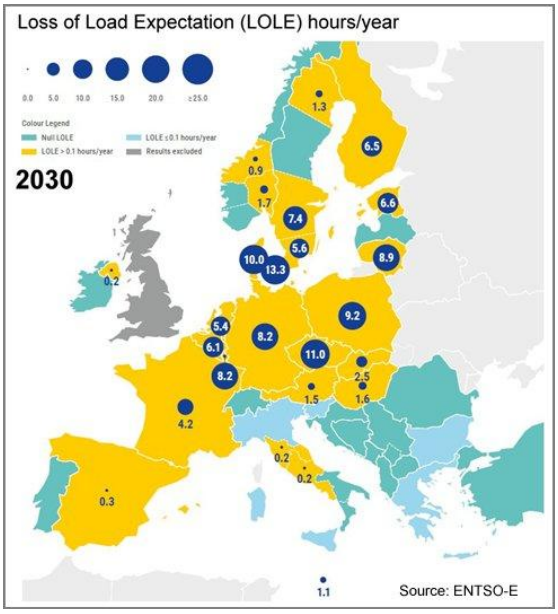

Fig. 6 - Calculated risk of power deficit

Compared to this calculation, it doesn't look so bad (Fig. 6), but in Denmark the electricity supply is more vulnerable than in other countries due to our low share of controllable production. Denmark cannot maintain a normal electricity supply without support from other countries, and in the event of a grid failure the system probably cannot be started without outside help.

Market analyses indicate that support from neighbouring countries will become more expensive over time, while Danish surplus production will become worthless.

Added to this is the vulnerability caused by the many installations at sea. They are difficult to defend and can be relatively easily put out of action by systematic sabotage carried out by a party with sufficient knowledge and resources.

One can choose to live with these vulnerabilities, but it is important that the associated risks are known and understood.

Analysis assumptions[3] ignore market conditions and network planning

The annual analysis assumptions were made by Energinet up to and including 2017, but from 2018 the Danish Energy Agency took over the task.

The Danish Energy Agency must specify Denmark's objectives for the electricity infrastructure. The Danish Energy Agency explains that on this basis, Energinet must, among other things, carry out the necessary analyses of markets, networks and security of supply. The problem with this division of labour is that there is apparently no possibility of feedback if Energinet's analyses reveal shortcomings or inappropriateness in the assumptions.

Thus, Energinet has tried to show in its public communication that the large proportion of production with low utilisation time means a larger installed production capacity and thus an extensive infrastructure expansion, which will be difficult to implement within the given timeframe.

The obvious solution to this problem is to give Energinet a more central role in the preparation of the analysis assumptions, so that both market analyses and infrastructure planning can become a natural part of the process.

[3] The Danish Energy Agency's "Analyseforudsætninger til Energinet 2024" (AF24)

AF24 consists of a summary note, a large spreadsheet and a number of background reports. It is a comprehensive material. The analyses in this article do not include all the details, but should be seen as an interpretation of AF24.

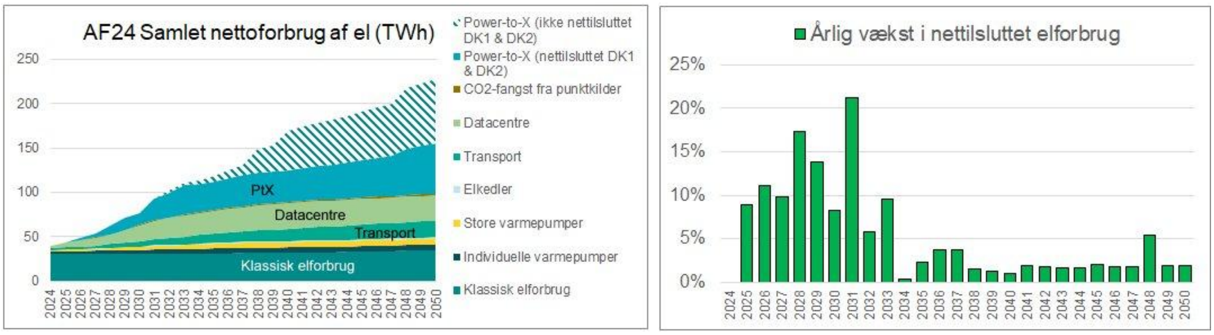

Fig. 7 – AF24: Data centers will be the 3rd largest grid-connected group of electricity consumption in 2050

Danish electricity supply from stagnation to expansion

After many years of stagnating electricity consumption, Denmark will enter a phase of strong expansion of grid-connected electricity consumption from 2025.

The composition of electricity consumption until 2050 paints a picture of the expected development until 2050 (Fig. 7). An annual growth of around 10% for grid-connected electricity consumption over a number of years will put pressure on the Danish labour market and international supply chains.

The analysis assumptions do not contain a comprehensive overview of installed capacity and produced energy, so this is where the interpretations begin (Fig. 8). The power diagram shows solar cells as the largest group with 45 GW in 2050. This is more than half of the installed capacity and a tenfold increase compared to the level in 2025. This should give food for thought when looking at how the production of solar energy changes the daily price profile in the electricity market. On the energy side, the relationship is the opposite. Here, wind energy accounts for over half of production.

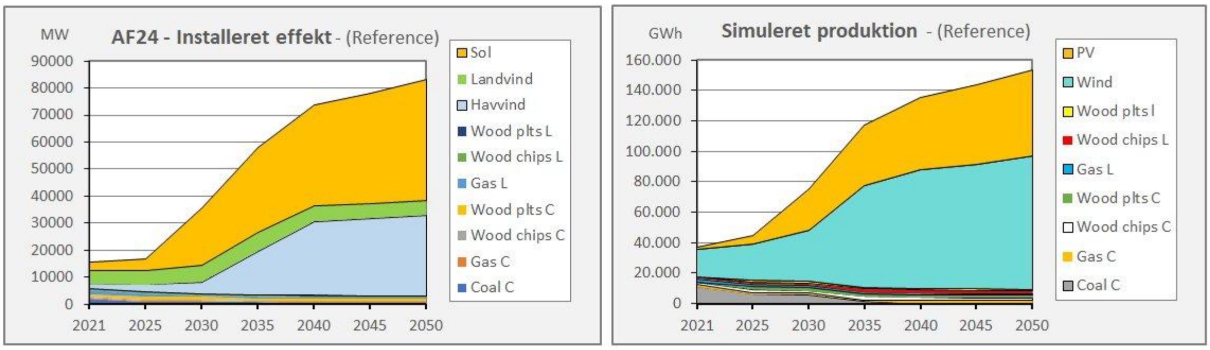

Fig. 8 - In the explanations, "L" stands for "local" and "C" for "central". Grid-connected systems only.

Flexible demand must ensure utilization of uneven production

The simulation model includes Power-to-X (PtX), electric boilers and large heat pumps as flexible consumption, of which PtX in 2050 constitutes over 80% of the expected consumption of 68 TWh.

In simulations, 63.3 TWh have been delivered for a capacity of 23 GW, i.e. slightly less than expected in AF24. The capacity factor for the entire group is 31.4% in the simulation, where AF24 has assumed 33.6%, of which 38.3% for PtX, 10.9% for electric boilers and 52.9% for large heat pumps.

2050	GW	TWh	Cap.fac.
PtX nettilsluttet	16,8	56,2	38,3%
Elkedler	4,8	4,6	10,9%
Store varmepumper	1,5	6,8	52,9%
	23,0	67,6	33,5%

Fig. 9 – AF24 - Flexible consumption 2050

The order of magnitude of the capacity factor should be seen in relation to a non-grid-connected electrolysis plant with its own offshore wind farm, which can expect a capacity factor of between 40% and 45%, varying from year to year.

The energy balance for 2050 can be drawn up based on the simulated results (Fig. 10). The results largely confirm the expected distribution in Fig. 8.

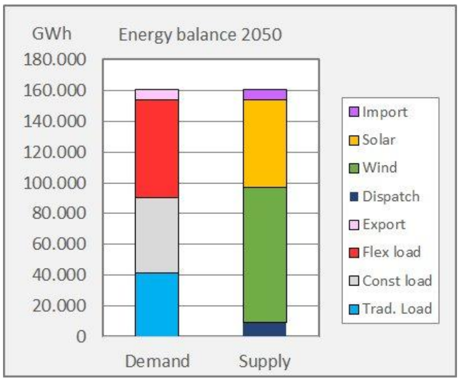

Fig. 10 - Simulated energy balance 2050

Fig. 10 shows the unchanged classic electricity consumption of around 40 TWh. Part of the constant consumption is data centres, which with 29 TWh in 2050 are expected to constitute the 3rd largest consumption group after PtX and classic electricity consumption.

The simulated overflow in 2050 is 7.2 TWh, which will probably be worthless. Production from wind turbines and solar cells will be disconnected as early as 2025 when the market price is zero or negative. This will mean lower production and correspondingly lower exports in 2050.

The import of 7.0 TWh looks like a trifle in the figure, but represents 2167 hours (almost ¼ of the year) of power shortage in Denmark and probably also in neighboring countries. It is considered a power shortage when classic and fixed consumption cannot be covered with domestic resources. The vulnerability of the system, which can be observed already in 2025, will not decrease. This will be especially evident if there are new shifts in the sensitive balance between supply and demand, e.g. due to delayed construction projects.

More dispatchable production benefits self-sufficiency and robustness

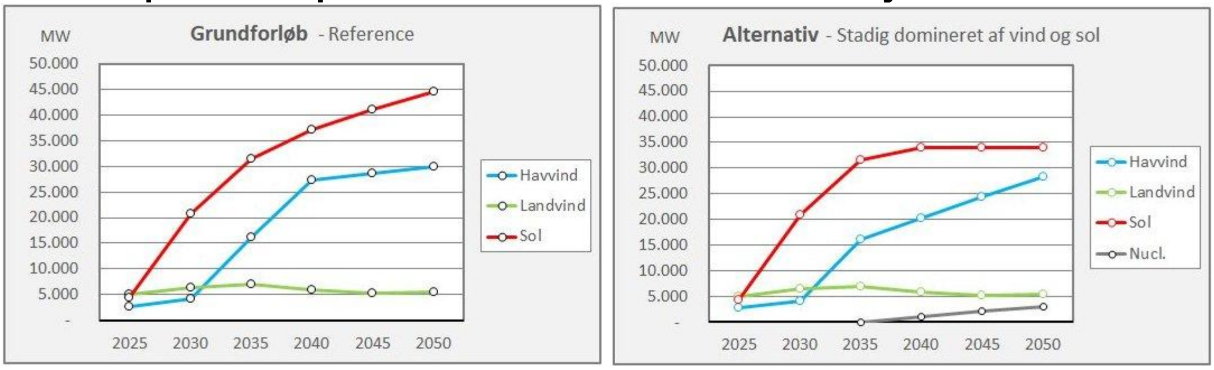

Fig. 11 - Capacity of wind power and solar cells in AF24 basic scenario and in alternative with nuclear power

The thesis that there is no room for nuclear power in Denmark is tested in an alternative simulation, where 1000 MW of nuclear power is added in 2040, 2045 and 2050 (Fig. 11). At the same time, the growth of solar cells is reduced by 10.6 GW and the growth of offshore wind by 1.6 GW, which gives a total capacity saving of 9.2 GW. This achieves roughly the same coverage of flexible consumption and an assumed saving in infrastructure.

Fig. 11 shows that the capacity of onshore wind is expected to be fairly constant throughout the period, and that nuclear power does not occupy that much space in relation to the capacity of wind and solar power.

The simulated results for 2050 are intended to illustrate the differences between the baseline scenario and the alternative.

		Grundforløb	Alternativ
System		2050	2050
Dispatch	GWh	9.466	25.798
Shortage	Import		
	GWh	6.980	2.918
	hours	2.167	1.377
Overflow	Export		
	GWh	7.198	1.936
	hours	894	403

Fig. 12 – Reduced power outages and overflows

Fig. 12 shows that the dispatchable production has increased due to nuclear power, and that both electricity shortages and electricity overflows have been reduced noticeably.

The 3000 MW nuclear power has delivered 21,070 GWh, which gives a capacity factor of 80.2% (fig. 13).

	CO2	Capacity factor	
		Grundforløb	Alternativ
	kg/MWh	2050	2050
Gas C	237,6	22,2%	15,3%
Wood chips C	0,0	80,0%	21,3%
Wood plts C	0,0	24,5%	17,9%
Gas L	288,5	20,3%	13,2%
Wood chips L	0,0	80,0%	20,6%
Wood plts l	0,0	35,6%	19,6%
Nuclear	0,0	0,0%	80,2%

Fig. 13 - Full utilization of nuclear power

The production from wind and solar is 144,435 GWh in the reference and 126,914 GWh in the alternative. The difference of 17,521 is taken over by nuclear power. The rest is achieved by reduced use of wood chips and natural gas.

Could gas turbines solve the same task?

Nuclear power fits nicely into this example, but it is often claimed that it could be done better and cheaper with gas turbines. This is the case, for example, in the Climate Council's report on electricity supply[4].

Gas turbines have a much higher variable cost than nuclear power plants. Therefore, they have a completely different role in operation. In traditional load dispatch, the units are ranked according to marginal costs. A supply curve in an electricity market will normally reflect the marginal costs of the units. The supply curve, together with a demand curve, forms a price intersection, which determines the current market price.

In an hourly simulation program, operational optimization is done in the same way with the aim of achieving the lowest possible operating costs. This means that the market price of an hour is determined by a step on the supply curve or on the demand curve.

It may be interesting to study how many hours the price is determined by the individual units (price setting hours). This is therefore calculated as a result of the simulation (Fig. 14).

	Marg.cost	2050	Price setting	2050
Gas C	€/MWh	85,87	Hours	323
Wood chips C	€/MWh	55,97	Hours	79
Wood plts C	€/MWh	73,95	Hours	265
Gas L	€/MWh	114,53	Hours	132
Wood chips L	€/MWh	56,77	Hours	91
Wood plts l	€/MWh	73,65	Hours	106
Nuclear	€/MWh	24,00	Hours	0
Flex load	€/MWh	42,00	Hours	5984
Shortage			Hours	1377
Overflow			Hours	403

Fig. 14 – Price setting hours

[4] Sikker elforsyning med sol og vind - The Climate Council - May 2023

The amount of fluctuating power and flexible consumption makes the two calculated examples atypical. Nuclear power is introduced with a marginal price of 24 €/MWh. It has never been a determinant of the market price. On the other hand, flexible consumption has been for 5984 hours (approximately 70% of the year). Here the price is set at 42 €/MWh, which gives nuclear power the possibility of production up to the limits set by the need for inspection and repair.

A gas turbine would have a higher marginal cost than any other unit on the list. This would also include a CO2 cost. Therefore, the gas turbine would not be used to supply the flexible consumption. The beneficial effect of 3000 MW gas turbines would be to cover the power shortage to the same extent as nuclear power, but with a higher CO2 emission. The gas turbine, on the other hand, would not be able to replace the 1.6 GW offshore wind and 9.2 GW solar cells.

2050		Grundforløb	Kernekraft	Gasturbiner
Installeret				
Havvind	GW	29,9	28,3	29,9
Landvind	GW	5,5	5,5	5,5
Solceller	GW	44,7	34,1	44,7
Kernekraft	GW	0,0	3,0	0,0
Gasturbiner	GW	0,0	0,0	3,0
Andet	GW	3,2	3,2	3,2
Total	GW	83,3	74,1	86,3
Produktion				
Havvind	TWh	73,9	70,0	73,9
Landvind	TWh	13,5	13,5	13,5
Solceller	TWh	57,0	43,4	57,0
Kernekraft	TWh	0,0	21,1	0,0
Gasturbiner	TWh	0,0	0,0	4,2
Andet	TWh	9,5	4,7	9,5
Total	TWh	153,9	152,7	158,1
Ubalancer				
Elmangel	TWh	7,0	2,9	2,9
Overløb	TWh	7,2	1,9	7,2

Fig. 15 – Reference, nuclear and gas turbines

The calculated results for 2050 from the three simulations can be compared (Fig. 15). In the baseline scenario, the total installed power has increased sevenfold from 2025 to 2050. This major challenge for grid expansion can be alleviated by replacing the last part of the expansion with nuclear power. On the other hand, the gas turbine solution will result in greater installed power than in the baseline scenario and thus even greater grid demand.

A simpler method

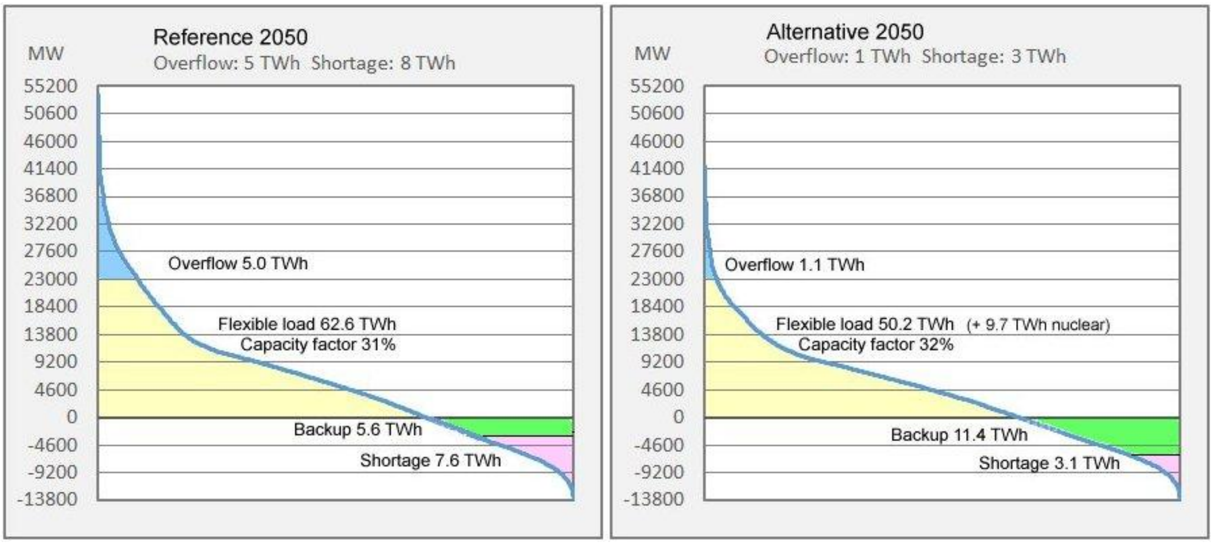

Fig. 16 - Duration curves for hourly values of fluctuating production minus prioritized consumption

For each hour of the year, weather-dependent production minus the prioritized consumption is calculated. The result is the surplus available for flexible consumption. For the 8760 hours of a year, the results form a series of numbers, which, after sorting from largest to smallest, form what is called a duration curve (Fig. 16).

In the examples, the flexible consumption is up to 23 GW. The yellow area up to 23 GW constitutes the energy supplied for flexible consumption. The blue area above 23 GW constitutes the overflow, which must be exported or interrupted.

Below the axis is the prioritized consumption, which must be covered. For this purpose, 3.2 GW is available in the basic scenario and 6.2 GW in the alternative. The red area constitutes the shortfall, which must be imported or interrupted.

Once you get used to this representation, you will see the delicate balance where a shift due to a delay in the construction site pushes the curve up or down and changes the year's surplus and deficit of energy accordingly.

The simulation model is in some areas more detailed, for example with the representation of batteries. Therefore, there are smaller differences between the results of the two methods.

Scenario analyses can reveal vulnerabilities in electricity supply

It is important to be prepared to operate the electricity supply under conditions that are outside the stochastic variations included in the calculations described. Scenario techniques are used for this purpose.

A simulation for an electricity system usually covers a number of years and illustrates a smooth development from the first year to the last. In this way, certain properties can be illustrated. Reality is not smooth. It never has been. Fluctuations can occur and, in rare cases, discontinuities. A decision must be made as to which measures can be used to handle the unexpected deviations.

The method assumes that a limited number of scenarios are selected. Each scenario must pose a serious challenge. It could be an economic crisis with restrictions on international trade. It could be an energy crisis where all countries first take care of themselves and thereby reduce mutual support. Or it could be an international conflict with acts of war and sabotage. The scenarios must be so different that they cannot be bent by degrees, because then it becomes a sensitivity analysis.

Scenarios can be called the bad news of the future.

The method may show that some scenarios are so severe that one chooses to establish a degree of preparedness to mitigate the effects. Permanent preparedness costs money. That is why it is important that decision-makers actively participate in the process.

Recommendations

The exclusion of nuclear power from the planning of the future Danish electricity supply has made the solution space unnecessarily narrow.

- The bans on nuclear power in Denmark should be lifted.
- The planning should include a broader spectrum of solutions than before to ensure better choices for political decision-makers.
- The planning should be based on broader expertise than before, including an understanding of international markets and infrastructures, which is why Energinet should

play a central role. In addition, there is a need for expertise and experience with all relevant production technologies.

The desire to multiply Danish electricity supply in 25 years at the same time as the conversion to almost 100% wind and solar energy may encounter practical and commercial barriers.

- Information should be provided openly and adequately about the progress of the conversion.
- When important interim targets are not met, the plans should be updated in a more realistic direction.

The conversion to more weather-dependent production will change the characteristics of the system.

- The reduced flexibility will reduce the commercial opportunities for Danish electricity traders and thus create greater economic uncertainty for Danish electricity consumers. An appropriate minimum of domestic flexibility should be maintained on both the supply and demand sides.
- The safety limits in operation are changing. The current limits are based on decades of experience from all over the world. This collection should be intensified so that sufficient operating reserves can always be maintained, also under the new conditions.

Vulnerability and preparedness have gained new relevance.

- It is recommended that the robustness of the electricity supply under extreme conditions be tested using scenario techniques and that, as a result, the preparedness measures deemed necessary are established.