

The Danish Energy Transition

By Søren Hansen

Introduction

Denmark is a small country in the World; 6 million inhabitants and the yearly greenhouse gas emissions constitute roughly 0.1% of the global figure. Nevertheless, the government has set ambitious targets for the road towards “net zero” in emissions. By 2030 these should be reduced by 70% compared to the figures for 1990, and by 2045 or 2050 Denmark is to achieve so-called “climate neutrality”.

Obviously, these measures will have negligible impact on the global situation, but the rationale is that Denmark wishes to play the role of frontrunner. The rest of the World will see that achieving such ambitious targets indeed is possible, and then they will follow the good example and Earth will be saved from the climate catastrophe.

Reaching “net zero” requires action over a broad field of activities: industry, agriculture, heating, transportation and of course the electricity supply. The following report will focus on the latter, and this is also the area where we see most progress towards achieving the climate targets so far. Now, electricity at present only accounts for around 20% of the total energy consumption, but the climate ambitions entail converting a large part of the other energy use to electricity. Battery electric vehicles and heat pumps for housing are prime examples of this development.

Development since 1990

Denmark traditionally got the electric power from oil-fired power plants. Following the energy crisis in the 1970-s the country diversified into coal. Oil and gas were found in the Danish sector of the North Sea back then and the gas also became a fuel for power plants, especially smaller decentralised generators, combining power production with district heating. An extensive pipe network was established in order to furnish residential areas with gas for heating.

All the larger power plants were furnished with district-heating installations, rendering the energy efficiency of the Danish power sector very high. By 2010 the vast majority of the housing was heated either by natural gas or by district heating. Oil-fired boilers would primarily be found in more remote areas outside the reach of the distribution systems.

Nuclear power was considered for Denmark in the 1970-s but abandoned finally in 1985 by a vote in the Danish Parliament.

Instead, the focus shifted to renewable energy, where the first electricity-producing wind turbines were set up all the way back in the 70-s. However, it was only in the late 1990-s that this technology began to contribute significantly to the Danish power supply, as shown in fig. 1. Since then, there has been a gradual increase in the installed capacity of the wind turbines, and in 2023 they produced a total of 70 petajoules, which corresponds to roughly 10% of Denmark’s total energy consumption that year. Solar power had a much slower start, but took off after 2010.

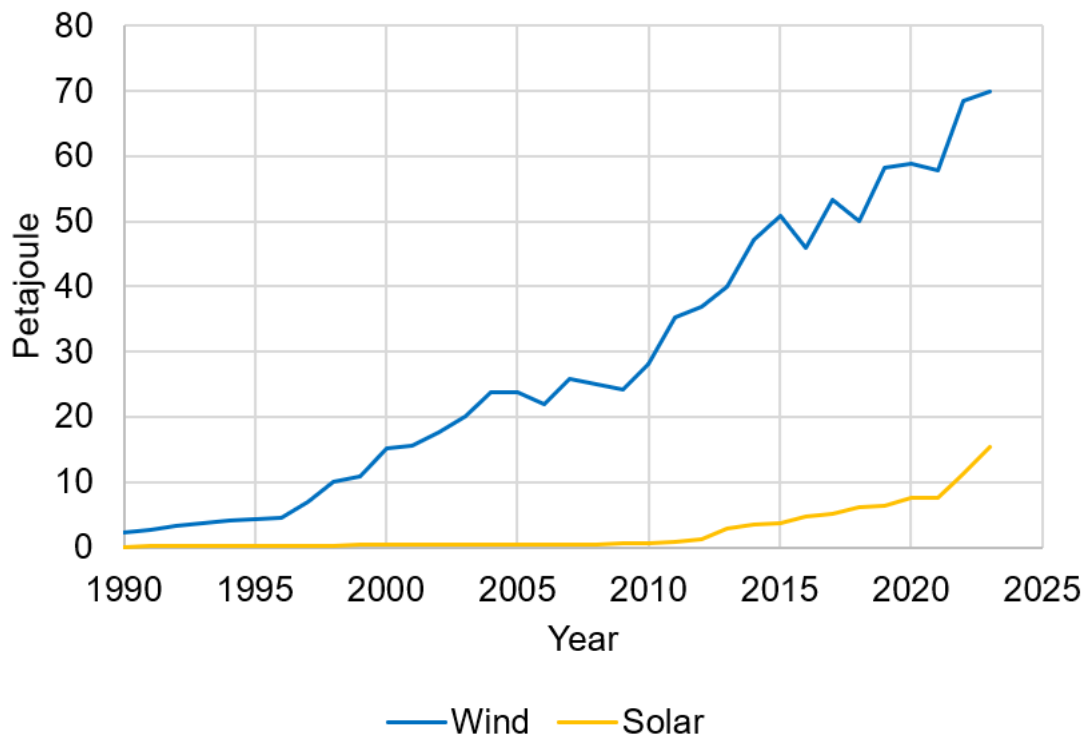


Fig. 1. Production of electricity from wind and solar in Denmark, 1990 to 2023, in petajoule. Data from the Energy Agency¹

Wind turbines

Fig. 2 shows the development over the years in the installed capacity of wind turbines. The increase over the years has been varying, depending on the economic and political situation. Initially, a large number of small turbines were installed on land, and at present the total number onshore exceeds 5600. The development on land has slowed down significantly during 2022 and 2023, mainly due to local resistance from the potential neighbours to the turbines. The procedures for approval comprise many steps and are complicated and bureaucratic.

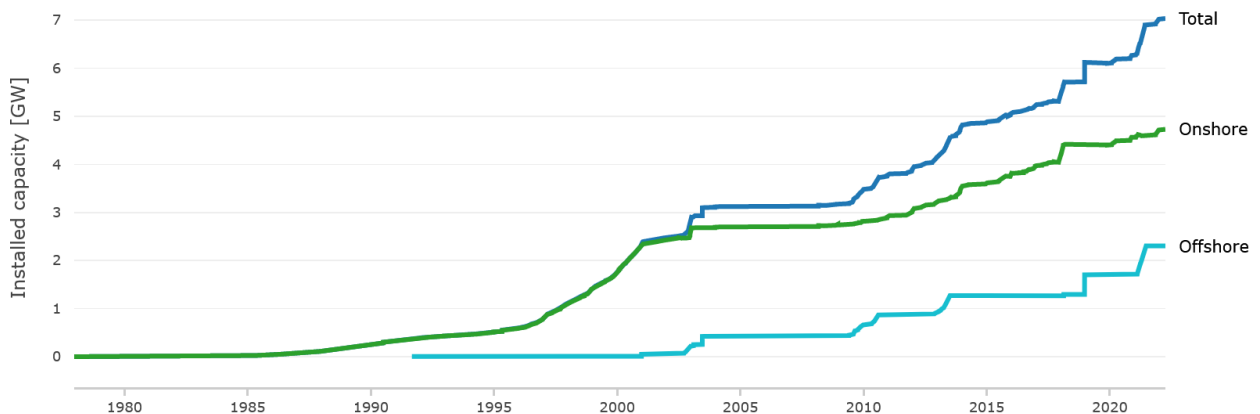


Fig. 2: Capacities of Danish wind turbines, in GW. Source: Turbines.dk²

The very first offshore turbines were put up already in 1991, but since 2002 the number started to increase in steps, reflecting that the offshore turbines are put up in farms of 10-100 units.³ From fig. 2 it can be inferred that since 2014 only two new wind farms have been installed. More projects were in the pipeline, but have been stalled by various environmental concerns, including considerations of biodiversity habitats. Fig. 3 shows the existing offshore wind farms together with some of the planned projects. By 2023 the total number is around 630 turbines.

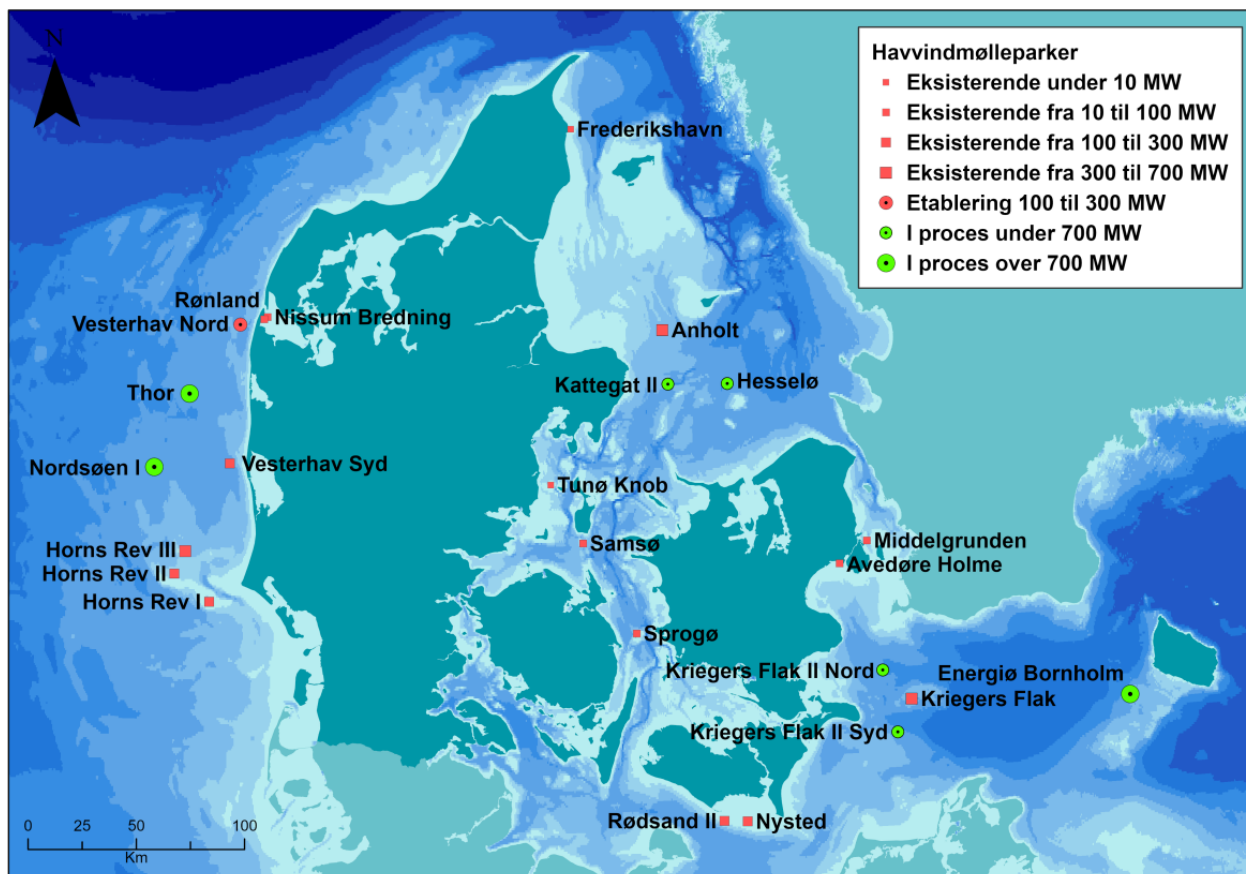


Fig. 3: Offshore wind farms as per 2024 (red squares) as well as a selection of projects in various stages of planning (green circles). Image: the Energy Agency⁴

The total capacity of wind turbines in Denmark is now 7 gigawatts (GW), which is well above the average electricity consumption of around 4 GW.

Solar cells

Fig. 4 shows the development of solar energy. Here, the capacity development only took off in 2011; before then there were only a smaller number of panels on the roofs of private homes. After a steady increase, the capacity suddenly took off in 2022, but again slackened in 2023. The reason for the slowdown was the changes in the policy of the national energy distributor, Energinet. From 2023 the solar farm developers were obliged to pay at least part of the cost of connecting their plants to the public grid. This turned out to be a problem, since many solar farms were located wherever land was available, with no consideration for the issues with hooking up to the grid.

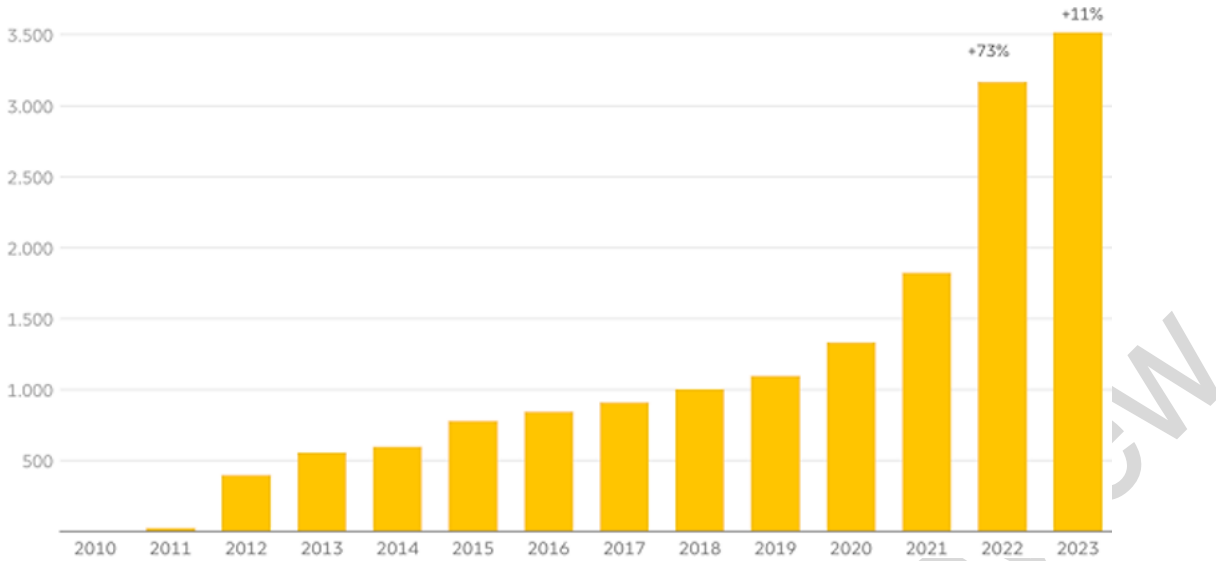


Fig. 4: Development of solar installed capacity in MW, 2010-2023. Chart: TV2⁵

Denmark is located on a fairly northern latitude, and often has cloudy weather. The result is a marked difference between the solar production during the summer and in winter. Fig. 5 shows the production realised in 2023, where the contrast between summer and winter is profound. In fact, the monthly production during December is only around 10% of the summer output, and at the same time, the electricity consumption is considerably higher.

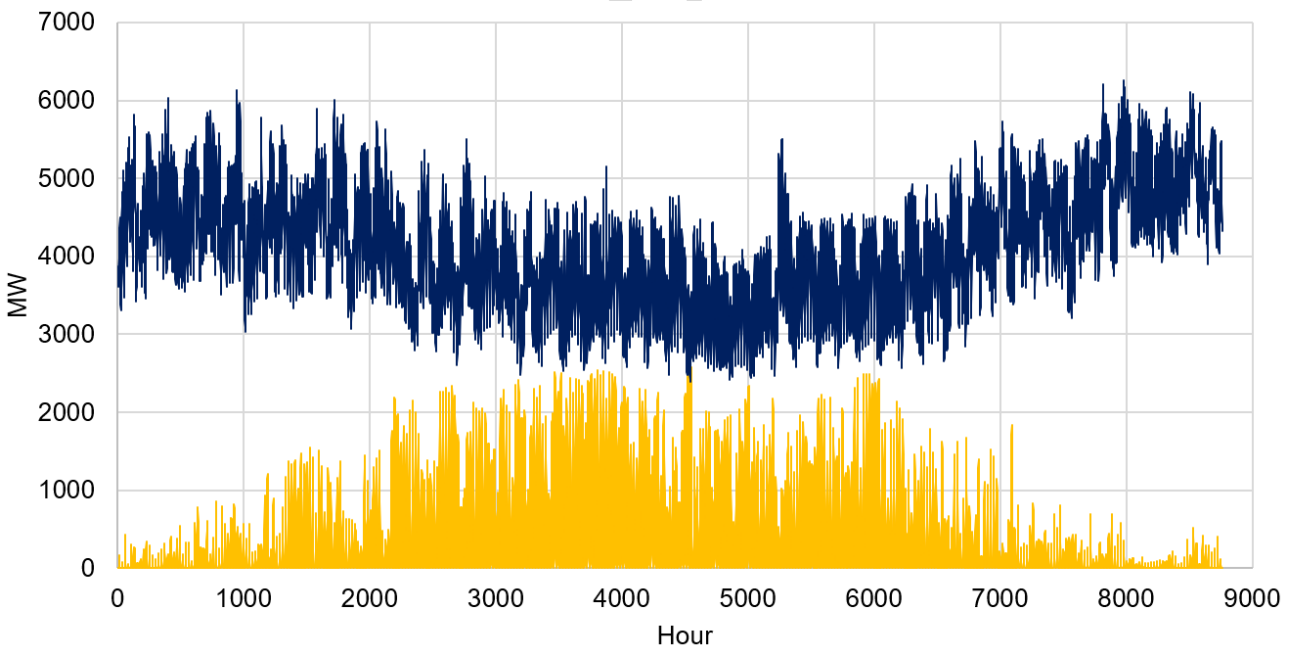


Fig. 5: Hourly power consumption and output from solar cells in Denmark 2023. Data: Energinet⁶

By late 2023 the total capacity of solar cells installed was close to 3.5 GW, bringing the total of renewable energy capacity to around 10.5 GW, or 2.5 times the average power consumption in the country.

Financial aspects of wind

Initially the wind turbines in Denmark were put up individually, or in small groups and owned by small companies or gatherings of private investors. Some of the projects were based on selling the electricity at the going market rate, while others secured fixed-price contracts. In practice this was often done using the Contract for Difference (CfD)⁷ model, where the turbine owner would receive a fixed amount per kWh produced. If the market price was lower, the government would cover the difference, while a higher market price meant that the owner should pay the surplus to the state. In this case, the turbine operator runs no risk apart from the initial investment. The income is fixed throughout the contract period, and hence the return on the investment is secured.

The same model was applied on most of the earlier large-scale offshore wind-turbine farms. The government would select the site and then ask the investors for bids on the CfD rate. Thereupon the risk from market price fluctuations would be assumed by the state. The turbine operators only had to ensure that the wind park was built within the budget, and that the production turned out as expected.

But the bidding process carried some risks on its own. In order to secure the contract, bidders were tempted to offer low prices, based on optimistic construction costs and high expected output from the turbines. According to a British study⁸, the consequences for the latest completed wind park in the Baltic (Kriegers Flak) are that the project actually is not financially viable, and the owners, whoever they might be, will end up losing money.

However, this was not realised when the latest large wind farm, named Thor, was put on auction in 2022. With a capacity of 800-1000 MW, and located 20 km out in the North Sea, the conditions for the bidders were quite strict. The winner would as an entry fee have to pay a fixed sum of 2.8 billion DKK (320 million £) to the government over the first few years of operation. The bidders now had to define which minimum price they would accept as a guarantee. Optimism abounded and the six bidders all came in with zero as guaranteed price.

The Danish Energy Agency was delighted and simply drew lots⁹ to find the winner, which turned out to be a consortium led by a German company. This result left many people wondering. Why did the Agency not permit negative bids, i.e. offers to pay more than the 2.8 billion DKK? That would have ensured a fair competition and more income for the state. Also, the 6 offers were not evaluated on their merits, one participant, Ørsted, had actually carried out extensive pre studies in the area, whereas the lucky winner had done nothing, and would only start the work after winning the contract – which incidentally still was not binding for him.

The Thor project is based on the operator earning whatever the electricity market will offer during the next 30 years. All the risk is thus assumed by the investors.

Denmark had another scheme called “Open Door”, whereby wind operators could reserve for themselves an area of the sea, where they could build their wind farm with no government subsidies whatsoever, but no payment to the government either.

In the years of extreme optimism before 2023, the wind project developers suddenly saw golden opportunities here, and within a short time, the Energy Agency found itself with more than 30 applications. Wind farms were to be set up along all the coasts of Denmark, as shown in fig. 6.

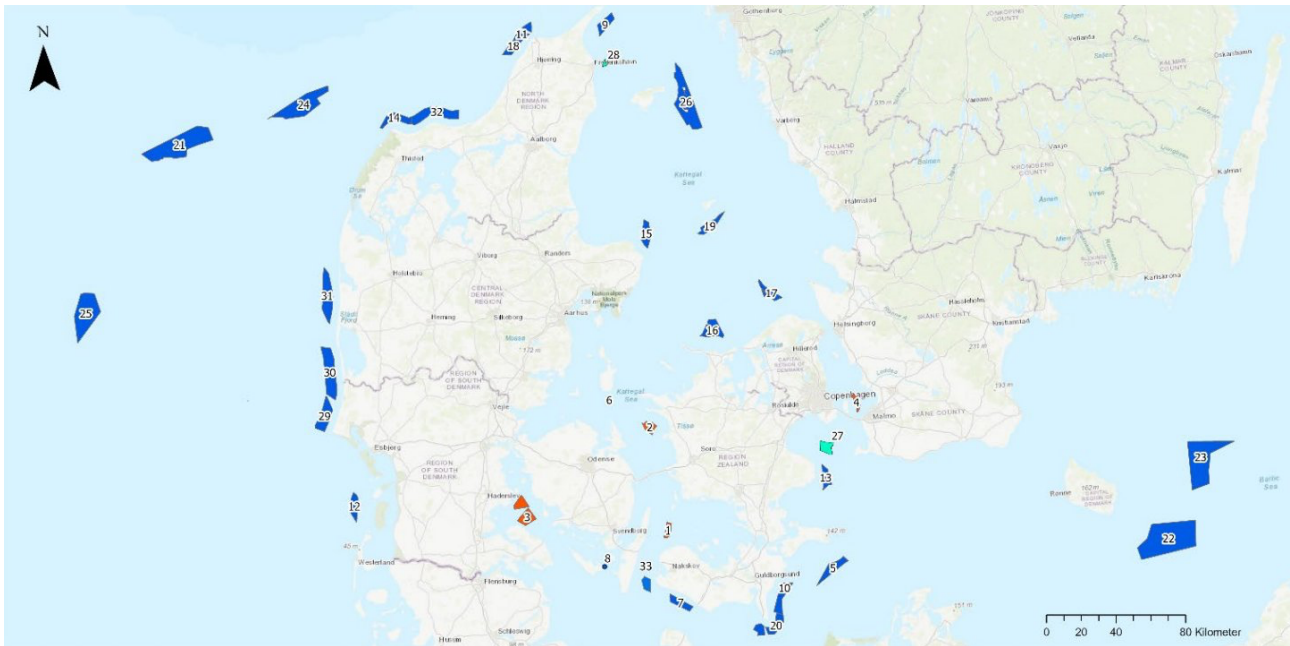


Fig. 6: Plans for wind farms under the “open-door” scheme. Image: www.energy-supply.dk¹⁰

Apparently, the government got cold feet and it was decided to terminate the Open-Door policy. The excuse was that the EU probably would regard the proceeding as unlawful government financial support, which would skew the competition. The setup died quietly and even some projects that had advanced quite far in the permitting process were cancelled.

The government by then saw the potential for a substantial income from wind farms, and the idea now was to introduce concession payments, like the country had had for the oil and gas exploration in the North Sea. Future wind-turbine operators would now have to pay yearly fees for the areas occupied and the auctions would be decided by whomever offered the largest yearly payments.

And then the crisis in 2023 hit. Fierce competition in the wind-turbine business had driven the prices down to a level where the Western producers like Vestas, Siemens Gamesa or GE were losing money with every turbine sold. Price hikes of 30-50%¹¹ had to be implemented in order for the companies to turn a profit again. At the same time, the interest rate, which had been zero for a number of years and ensuring a very low financing cost, rose up to something like 4%. This is very serious for a wind farm project, since all the costs basically are held during the construction period, and the income only comes in later, spread over many years. As a result, during the last year or so, we have seen numerous offshore wind turbine projects cancelled in the UK and US, the reason being that the agreed pricing was too low for any profitability of the farms.¹²

Now renegotiations are underway, and the agreed guaranteed prices are 50-100% higher than in the old contracts. This fact has not escaped the notice of the Danish operators and energy experts, and now the idea of concession payments seems more and more unrealistic.

In general, the terms of the wind contracts are not public knowledge. In principle, wind (and solar) always must have first priority to supply. After all, that is the whole purpose of the transition to renewable energy. However, there is a rising concern over what to do in the periods where the wind is blowing hard and the output of the turbines exceeds the national electricity consumption. Denmark is a small country and normally manages to export any surplus power. But if there are no takers – not even at negative prices, the next step is to stop some of the production. This is known

as curtailment. It has not so far hit Denmark seriously, but in Germany the northern half of the country often finds itself with far too much power from the turbines (and solar cells). In Germany turbine owners face serious fines if they stop the production, and hence for some years they have instead paid Danish operators to stop *their* turbines. The phenomenon is known as “countertrade”¹³ and a few years ago it reached something like 7%¹⁴ of the total Danish yearly wind-turbine production. This has been fine business for the Danes – earning money without wear and tear on their machines, but cost Germany a lot of money.

Before curtailment actually is employed, attempts are made to adjust the supply and demand by pricing mechanisms. As more and more wind turbines and solar cells are put up, negative prices are becoming increasingly common. Fig. 7 shows data on the spot prices in Denmark for 3 weeks in April 2024. Several times the price is zero, and on a few occasions, it dips below, with a minimum lower than -400 DKK pr. MWh.

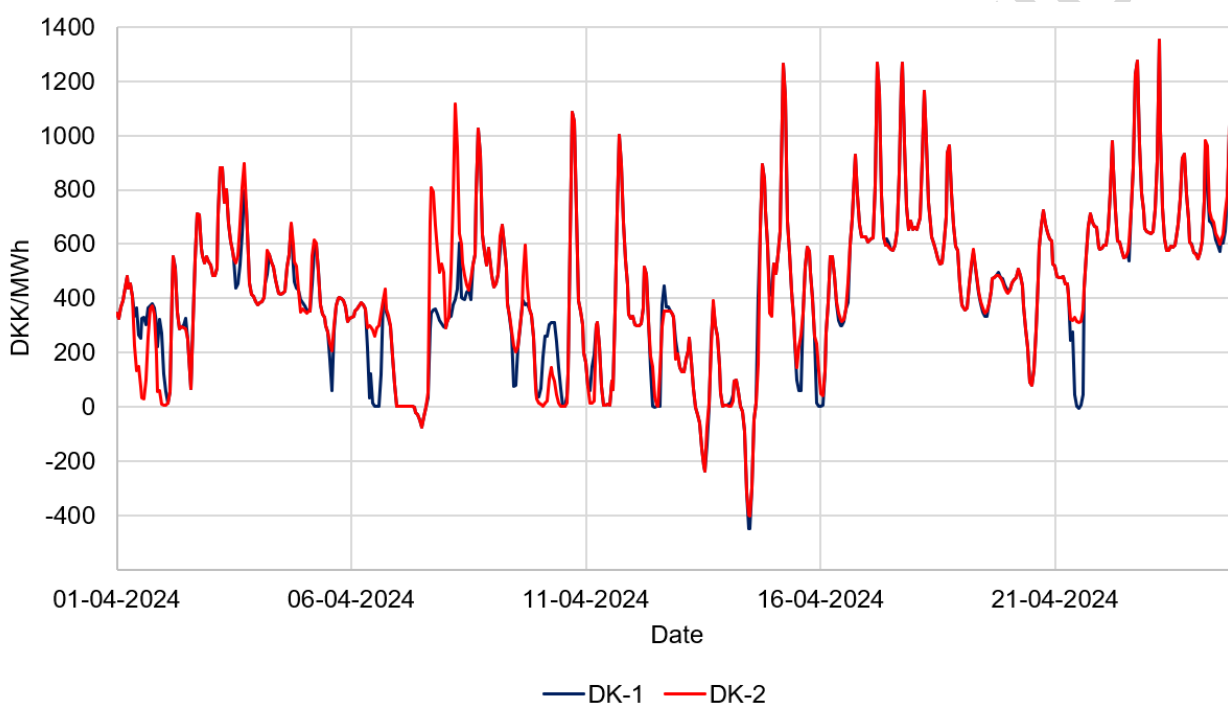


Fig. 7: Danish spot prices, DKK/MWh, April 2024. DK-1 is the western part, while DK-2 is the eastern. Data: Energinet¹⁵

The solar cell economy

Solar cells were initially mainly installed by private house owners or small businesses. The Danish government encouraged the initiative with very lavish financial conditions. If a house owner produced e.g. 5000 kWh during a year, he or she would be allowed to deduct all payment on the electricity bill for that amount of energy. The deduction included all taxes and network tariffs. So even though the production in summer was high and consumption low, the produced power would pay for the owner’s use during wintertime when the solar cells generated nothing.

Anyone investing in solar cells could make a lot of money on this scheme and it became very popular. However, by 2019 the government found that the indirect subsidies here were far too generous and costly for the public coffers, and the conditions were changed. Now only power consumed during the same hour as it was produced would be deducted from the electricity bill, the

rest would have to be sold on the market at going rates – which without taxes and tariffs seem quite low to the ordinary citizen.

The costs of electricity spiked after 2020 and this spurred a huge development of large-scale solar farms (ref. fig. 4). Agricultural land was rented by the project owners, and the rates were favourable to the farmer, compared to what he or she could earn by growing crops. Thousands of hectares were covered by solar panels and the development culminated in 2022.

Again, the contracts between the solar project owners and Energinet are not known in detail but in principle the solar farms will sell the power at market price. There are few CfD's involved here. The situation looked very lucrative anyway in 2022 with the high electricity prices, but these have fallen again, and further declines could jeopardize the economy of the solar farms. Furthermore, if the solar-farm owners are paid something resembling the hourly spot prices for the current, the problem will be that all the solar cells produce a lot at the same time (summer around noon), and this will drive the prices down, maybe even to negative values. In future, operating a solar farm might not be that profitable, this is a phenomenon also seen e.g. in California.¹⁶ The technical term here is that the solar farms are cannibalising each other.

The output from solar and wind

There is a widespread belief among politicians and decision makers in Denmark that the renewable energy sources will provide a steady supply of electricity. Of course, it is sometimes mentioned that the renewables are fluctuating, but there is no serious attempt to follow up on the issue. And yet, it is precisely this instability that eventually will sink the entire energy transition.

Denmark is not a large country by any standard, but there is still significant variety in the landscapes and weather conditions. The North Sea is considered rich in wind, whereas the average wind speed in the Baltic is considerably lower. The internal seas, e.g. Kattegat lie hemmed in by land. Onshore wind turbines in the western part of the country – Jutland – will yield considerably more energy than those in the eastern part, the island of Zealand, where Copenhagen is found. This is reflected in a marked imbalance in the number of wind turbines installed.

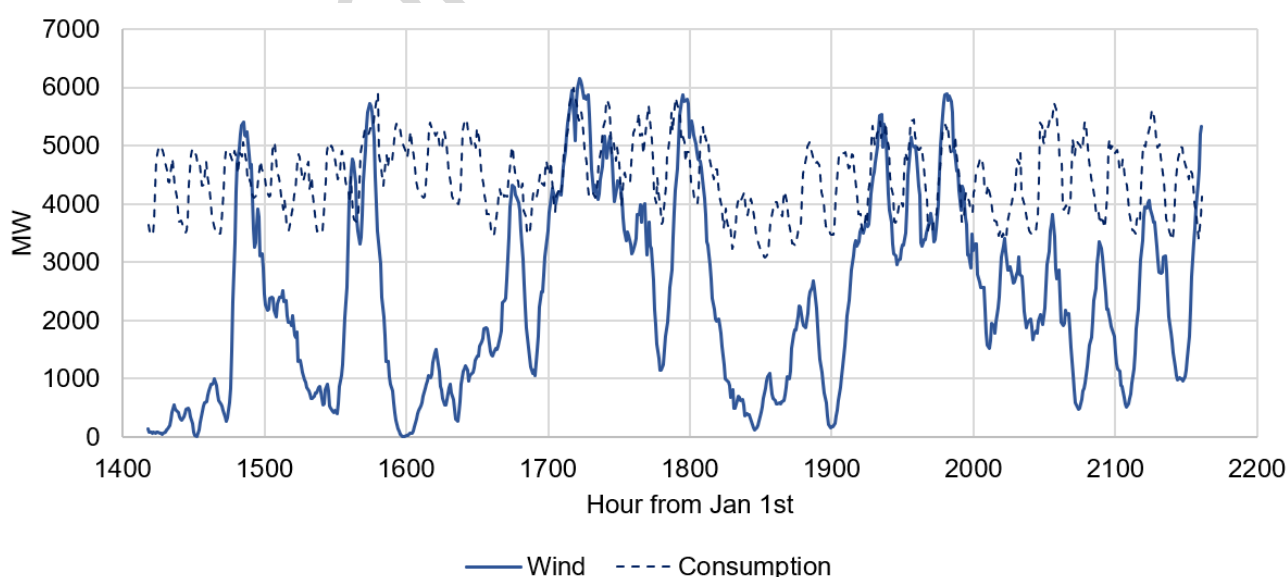


Fig. 8: Output from the Danish wind turbines in March 2023. Data: Energinet¹⁷

It is, however, notable how often variations in the wind will hit the entire area simultaneously, giving a tremendous day-to-day variability in the energy supply from the turbines. Fig. 8 shows the total production from Danish wind for the month of March, 2023. The total capacity installed is around 7000 MW, and on a few occasions the output exceeds 6000 MW. On the other hand, they also quite often give a very limited output, down below 500 MW.

On March 8 (around hour 1600 on fig. 8), the output reached a record low – across the entire country, from the North Sea to the Baltic, the turbines for a couple of hours supplied less than 20 MW, corresponding to just 0.3% of the capacity. What is remarkable is the steep fall in output, just the day before, March 7th, the turbines produced more than 5500 MW.

The curve in fig. 8 shows the general picture of wind power in Denmark. The production is never stable, but fluctuates constantly, often going from one extreme to another.

Adding the output from the solar cells does not improve the situation much. As mentioned above, the solar cells contribute very little in the winter months, so here our renewable supply would still basically come from the wind turbines. In summertime, solar will contribute a spike every day, but still nothing at night. Data for wind and solar combined during the month of June is shown in fig. 9. It is in this particular month apparent that there are many days with little wind, and the power supply is mainly the daily spikes from the solar cells. And even the output from these varies considerably from day to day, depending on the degree of overcast conditions.

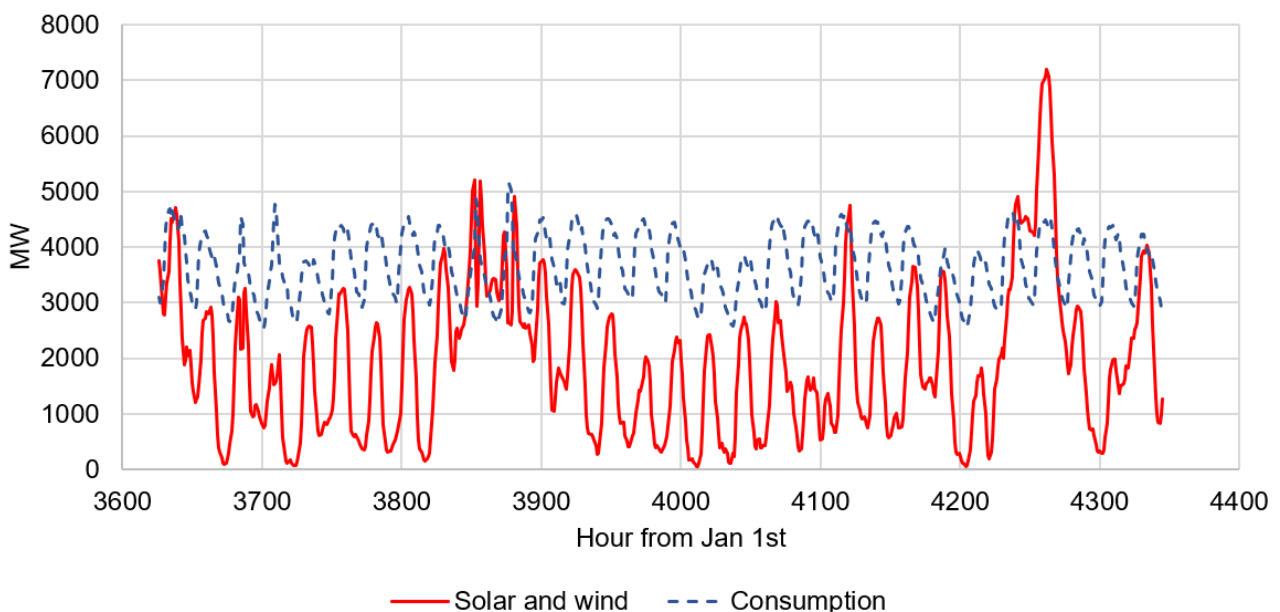


Fig. 9: The combined output from solar and wind in Denmark in June 2023. Data: Energinet¹⁸

Locally, the situation with clouds can aggravate the situation with the solar cells considerably. Fig. 10 shows an example from a 158 MW solar farm. The data is from just one day in October, where clouds come and go and the power output fluctuates wildly between 10-20 and 120 MW. Something else has to even out this supply, before it can be used on the grid, and the grid operator explained that every flexible reserve had to be employed in order to render the situation tenable.

Aktiv effekt målt fra solcellepark 11. oktober 2021

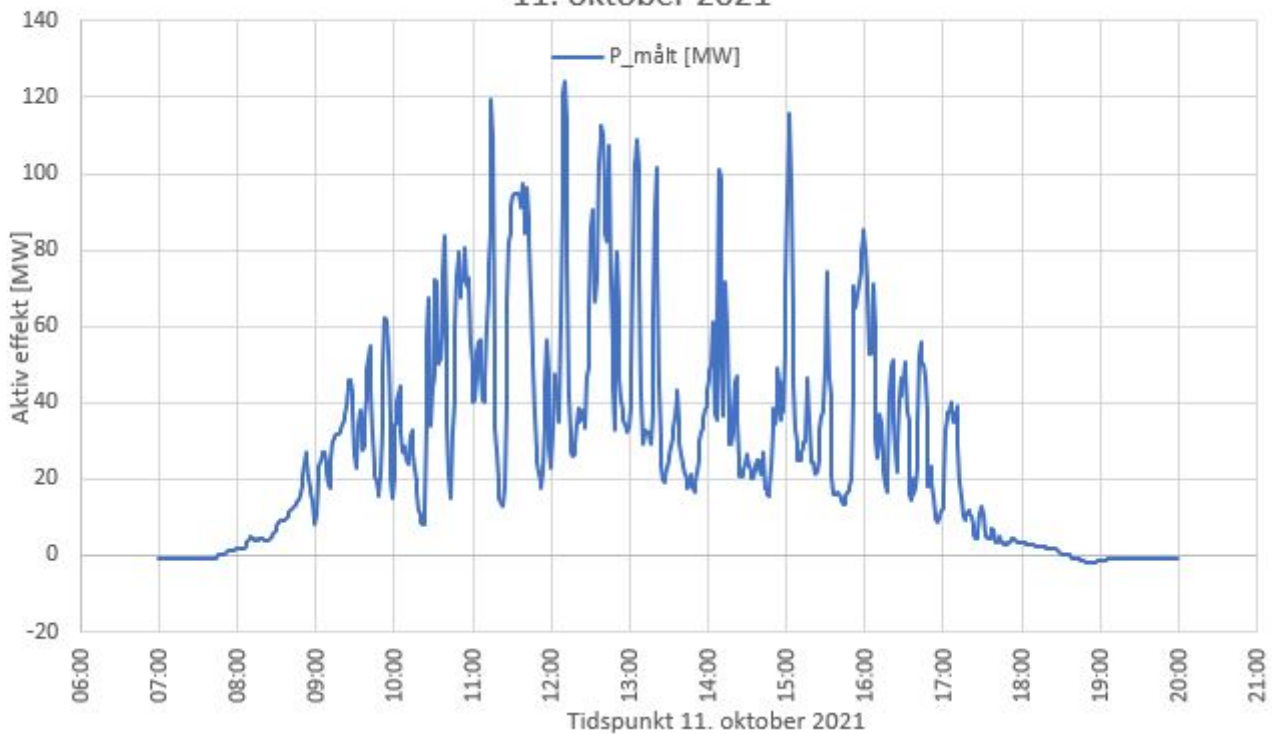


Fig. 10: Output in MW from one local solar farm during one day in October. Cloud cover changing continually leads to large fluctuations in the power production. Chart from Energinet¹⁹

There is a myth prevailing amongst Danish politicians and decision makers to the tune that we can “harvest” the green energy in vast quantities. Especially in the North Sea, where several hundreds of GW wind turbines are envisaged. This could turn the North Sea into the “Saudi Arabia” of Europe, providing an endless and inexhaustible supply of energy. However, the fact is that it will be a highly unstable supply, constantly varying and one day delivering hundreds of GW and the following day next to nothing. Obviously, any future power supply system must cope effectively with these issues if it is to be of any use.

Other sources of electricity

As mentioned, Denmark traditionally got all its electricity from fossil-fuelled power plants. Oil was replaced by coal and gas. Denmark was from 1999 onwards more than self-sufficient regarding gas supplies, both for power generation and heating purposes.

However, with the increasing awareness of the climate, a shift away from fossil fuels to biomass was initiated. Denmark had always used a fair amount of wood primarily for heating private homes. But now wood was introduced as a fuel for power plants, producing electricity and district heating. The aim was initially to phase out the coal. Several coal-fired plants were taken out of operation, one or two so thoroughly that the plants simply were demolished by explosives.

A number of other plants – coal or gas fired - were converted to biomass fuels, wood chips and pellets, or straw from crops.

Coal firing was to have ceased during 2020-2023, but the Ukraine war and following gas shortage in Europa lead the Ministry of Energy to request the restart and continued operation of 3 remaining coal boilers until at least 2024.²⁰

Denmark has an extremely well-working system of waste incineration. The need for landfill deposit is very small. A number of waste-handling plants will receive the waste, ensure sorting and burn everything that cannot be recycled. The energy generated is turned into power and district heating and provides a considerable contribution to the Danish energy supply.

Alas, this system is by now under severe threat as a result of – partly EU-inspired – vast recycling ambitions. The Danes at present have to sort their waste in 8-10 categories, and only a small part is in principle set aside for incineration. This does not always make very much sense. Mixed household plastics are virtually impossible to turn into new plastics, because of the many chemistries mixed together. We would be far better off burning the plastics, but now a lot is exported, ostensibly for sorting abroad, but in reality, ending up either in incinerators or as landfill...

Another issue is waste wood, from e.g. old furniture or construction timber. Here the ambitions dictate recycling into e.g. chipboards. Denmark has no capacity for handling the amounts of wood involved, hence the main part is exported. And at the same time wooden pellets are imported for generating power and district heating.

At present, the waste plants are short of fuel due to all this meaningless sorting. They have obligations to provide power and – in particular – district heating, so in order to keep running, they import significant amounts of waste from abroad. This is very beneficial since this material then does not end up in landfills, and hence makes up for our exports to landfills. However, the import is threatened by climate concerns, since the waste may contain e.g. plastics made from fossil oil. The future of the incineration plants thus is threatened, and plans have been made for closing a fair number of them. This is a very deplorable development, sacrificing an excellent system for some unfounded faith in a “circular” economy, which in practice cannot work as intended.

Denmark is paying dearly by now for all the green ambitions.

Biomass

Denmark is currently boasting that around 45% of the total energy consumption is now generated by renewables. This means that the country is well underway to the green transition and “net zero”. However, only a third of the renewable energy comes from solar and wind, which otherwise are considered the main sources of energy in the “net-zero” world. The remaining part of the renewable is generated from biomass, as shown in fig. 11. Five percent of the total energy comes from biogas.

Denmark has close to 200 biogas plants, some belong to individual farmers, others to cooperatives or energy companies. The raw materials for the plants are primarily waste, from industry or agriculture. The latter is for a large part constituted by animal manure and vegetable waste products. Some straw is used also. The biogas plants used in the past to receive an amount of energy crops, but the share of these has been reduced lately by government regulations.

The biogas contains around 30% CO₂, but this is for most of the volume separated off, and then the product can be mixed with natural gas in the national grid.

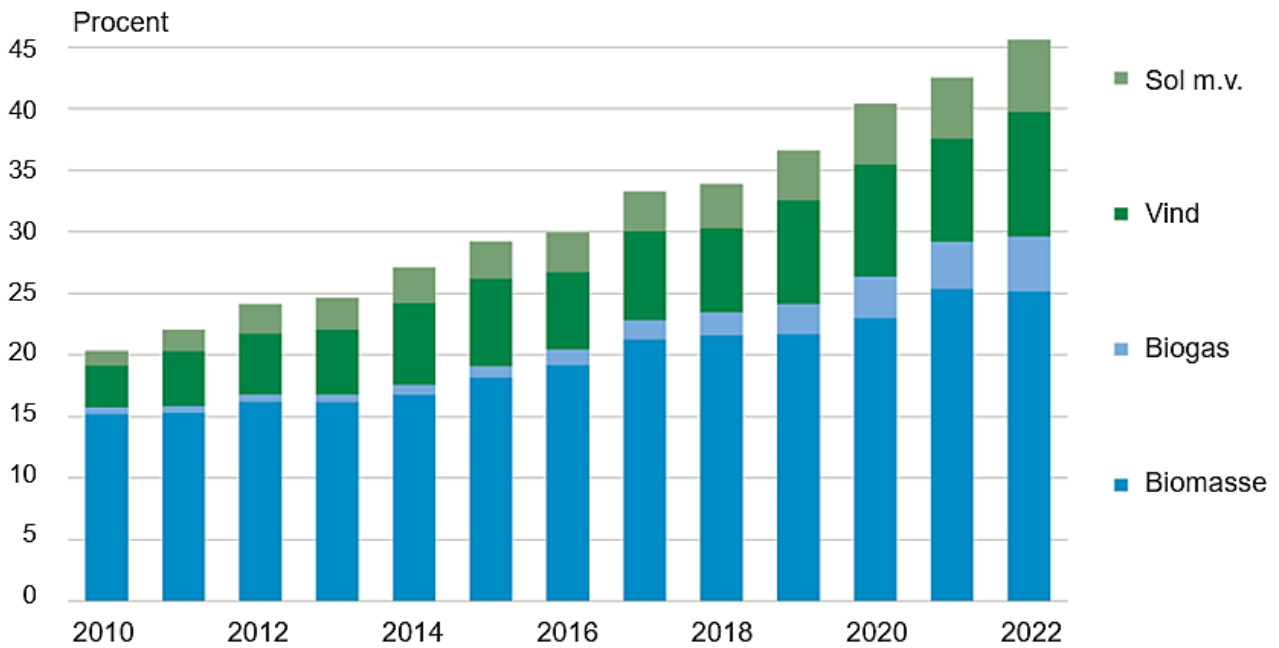


Fig. 11: Renewables' share of the Danish energy consumption. The total is more than 45%, but two thirds come from biomass. Chart: Danmarks Statistik²¹

The remaining biomass is chiefly wood products; fire wood, pellets or waste from forestry. Denmark used to cover the need by domestic production, but the climate ambitions lead to an ever-increasing amount used in power plants, and the country had to resort to imports. Fig. 12 shows the development since 1990.

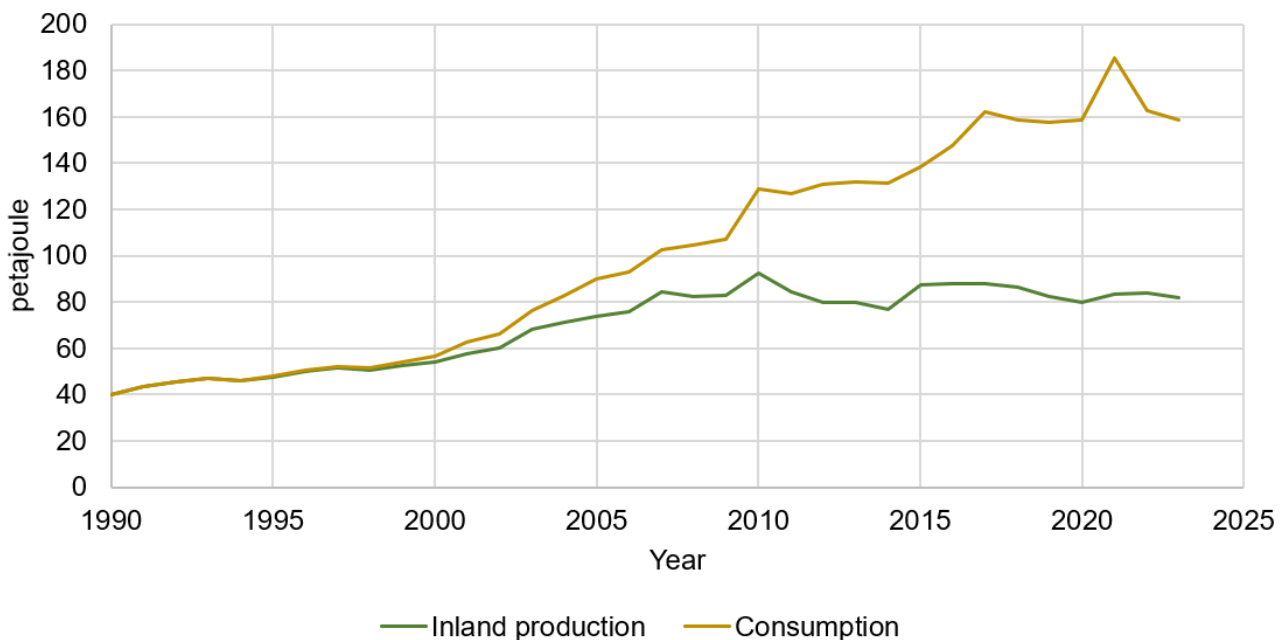


Fig. 12: Development in production and use of biomass in Denmark, 1990-2023. In energy equivalents (petajoule). The difference is covered by imports. Data: The Energy Agency²²

Until around 2000 the consumption did not exceed the domestic production, but then the former took off, and by 2023 it was around double the inland output. Denmark had turned into a heavy

importer of wood pellets and chips. Imports in 2022 amounted to 3.6 million tons of wood. The wood is purchased from e.g. the Baltic States and North America.

All of this is considered to be “climate neutral” and thereby does not emit any CO₂. This of course requires that all the trees cut down are done so “sustainably”, which in reality is rather doubtful in many locations.²³

Denmark wishes to be a frontrunner, but e.g. the IPCC²⁴ has pointed out that a sustainable consumption of biomass for energy purposes is limited to around 10-12 GJ per inhabitant. The current figure for Denmark is rather close to 30 GJ, three times what can be regarded as “sustainable”.

Balancing the electricity supply

Somehow the erratic supply from the wind turbines and solar cells has to be smoothed out in order that it matches the consumption second by second. The first line of defence obviously will be the power plants running on biomass and fossil fuels, the so-called dispatchable power. However, this is not a simple task. Obviously, they cannot help if the problem is too much production by solar and wind. On the other hand, especially during winter time they have an obligation to generate district heating, and hence they will be producing some electricity, whether it is needed or not.

But obviously they are called upon to compensate for the swings of the supply from solar and wind. Fig. 13 shows the output from the power plants over the year 2023. There is tremendous variation, from less than 100 to almost 3000 MW.

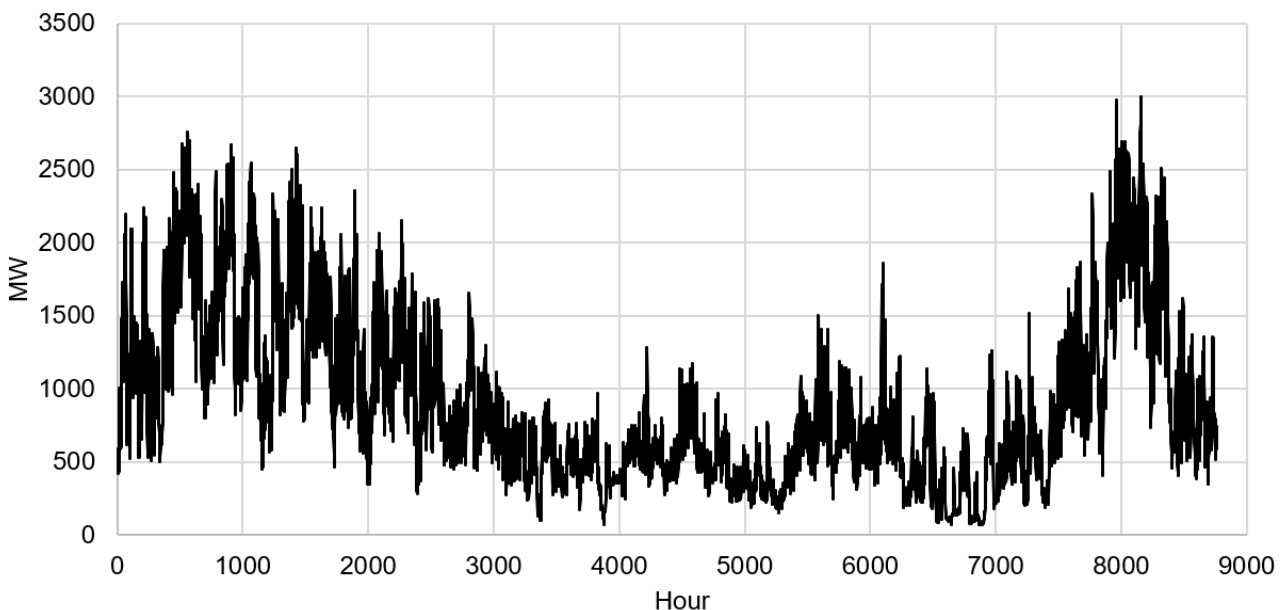


Fig. 13: Output from the Danish dispatchable power plants over the year 2023. Data from Energinet²⁵

Considerable flexibility is required of the performance of these plants, a more detailed excerpt from the curve in fig. 13 is shown in fig. 14. Here it is obvious just how big variations are needed within a few hours.

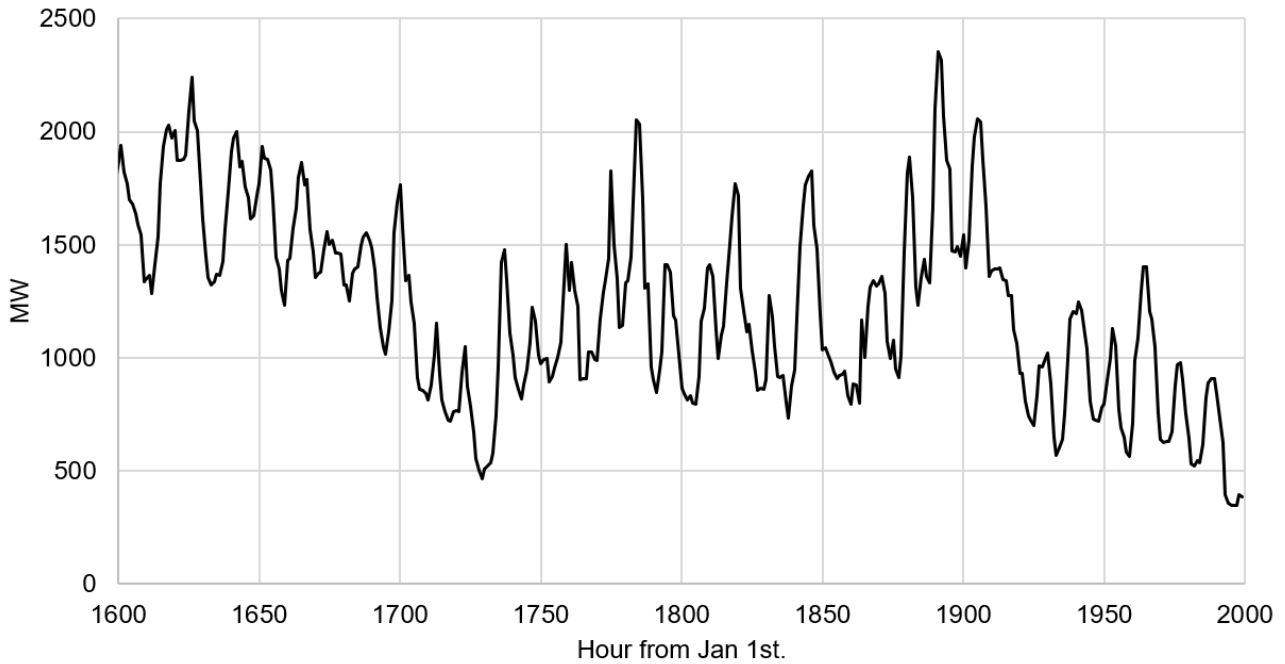


Fig. 14: Excerpt from the curve in fig. 13.

But in spite of these efforts, the situation is only saved by extensive imports and exports of power. Denmark has connections to five neighbouring countries, Norway, Sweden, Germany, the Netherlands and the UK.

Now, the picture becomes very complicated, because the foreign exchange of power does not only serve to stabilise the Danish domestic supply. Germany, the Netherlands and the UK all rely heavily on solar and wind power, and the wind tends to follow the same pattern over the whole area. Hence, when Denmark has no wind, neither has Germany nor the Netherlands. In this case, Norway and Sweden have to supply power from their hydro-electric and nuclear power plants. The power is sent southwards, passes through Denmark and ends up south of the border. When the wind blows well, Germany has a surplus of power, exports it to Denmark, which then forwards it to Norway and Sweden.

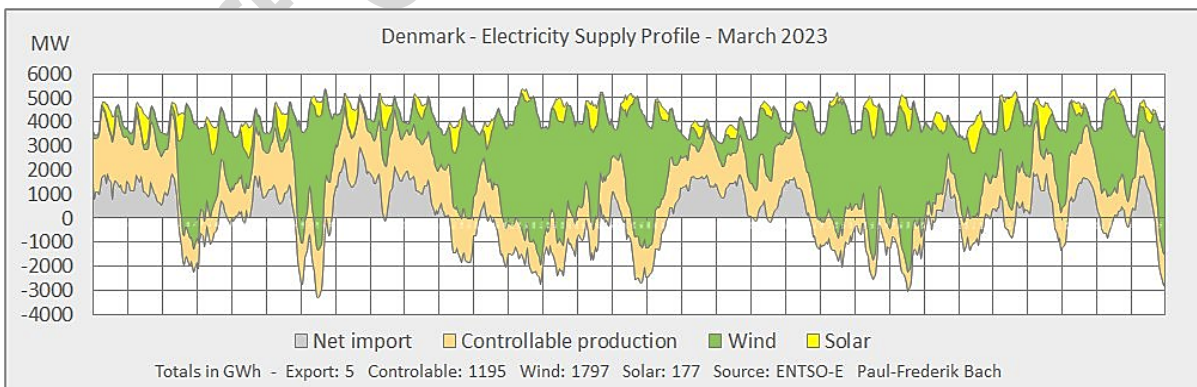


Fig. 15: Danish power production and need for import/export in March 2023. Chart: Paul-Frederik Bach²⁶

Hence the total yearly volume of exports and imports of Denmark far exceeds what would have been needed to ensure a balanced supply. However, day by day and week by week it is possible

to illustrate the situation as shown in fig. 15. Here, the production from the power plants, the wind turbines and the solar cells is shown. Whenever the production exceeds the demand, the curve drops below zero, indicating that export is required. In the opposite situation, where the domestic production does not match the consumption, import is needed, as indicated in grey.

On fig. 15 it is notable that the actual import and export are very large when at their peak. The maximum import thus exceeds 2500 MW, while the export reaches more than 3000 MW at one instance. These figures should be compared with the total power consumption of 3000-5000 MW. Denmark accordingly now and then relies on the neighbouring countries for more than half of the consumption, either as a surplus or a deficit. This is only possible because Denmark is a small country with a limited electricity usage. If a larger country, like e.g. Germany, aimed at the same solution, the neighbours would then sometimes have to receive or supply up to 40 GW, which of course is totally unrealistic.

The need for importing power is not only dictated by the availability of electricity from the power production. Actually, the decision on where the power is to come from is made in the so-called Nord Pool cooperation. The participating countries, see fig. 16, bring together producers and buyers in daily meetings where prices are fixed, hour by hour, region by region, for the following 24 hours. The producers are to offer the quantity of power they believe that they can supply – and at their marginal costs. The procedure is then that the cheapest producers are chosen first, and then the quantity of electricity needed is filled up with supplies from the more expensive producers, typically dispatchable power plants of various sorts.

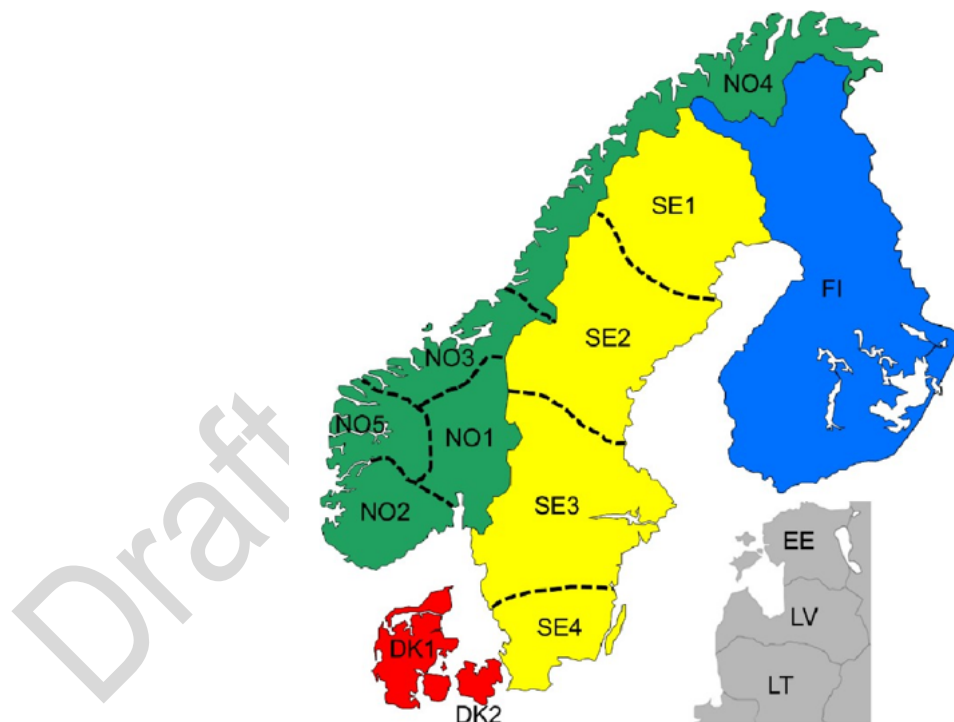


Fig. 16: The countries involved in the Nord Pool set-up. Some of the countries are divided into 2 or more regions, which then may have different power prices. Denmark has a parallel cooperation with Germany, the Netherlands and the UK. Image: www.ResearchGate.net²⁷

The going rate for the electricity will then correspond to the most expensive of the qualifying bids, and all the producers will receive the same amount. The system worked well for a number of years, where energy prices were stable, and solar and wind not too dominating sources.

The situation changed in 2021, when the prices of fossil fuels became much more volatile. The solar and wind operators normally always win their bids, since their marginal operating costs are close to zero. But the power plants had to offer according to e.g. the gas prices in the market, so their prices could be high. The prices could also fluctuate violently from hour to hour, depending on the availability of cheap solar and wind power, as shown in fig. 7 above. In all cases, the solar and wind operators faced windfall profits – unless of course they were tied down by a Contract-for-Difference or other fixed-price agreements.

But in 2021 and 2022 a lot of money was made, and it contributed to the euphoria regarding new solar and wind projects. The losers, of course, were the consumers, seeing their rates shooting up from day to day.

The electricity supply in Denmark is remarkably stable, blackouts are unheard of, except in connection with failure of local distribution equipment. But the national grid operator Energinet has expressed deep worries²⁸; the system is balancing on the edge now, and further expansion of the wind and solar capacity could well lead to insurmountable imbalances. A couple of incidents²⁹ have been described, where major network failures were threatening to materialize.

On the 10th of April, 2023, Germany found itself having a huge surplus of solar and wind power and was seeking to export up to 20 GW. Denmark was requested to take a large amount, and forward some of it to Sweden. However, Denmark also had a very productive day from solar and wind and really did not need to import anything. But Energinet was in the end forced to close down some Danish production and the owners were compensated with amounts reaching 18 DKK/kWh, approximately £2/kWh.

The next issue was on May 10th 2023. As usual, the producers had made their bids for the following 24 hours' prices and quantities. It was known from the weather forecast that the wind speed would drop during the day, and the wind turbine owners had offered accordingly. However, the drop occurred 4 hours earlier than forecast, and then Energinet found itself desperately short of power. Only by scraping the bottom of the barrel did they manage to round up enough power, but at costs up to 40 DKK/kWh, more than £4/kWh. The situation was very close to brown-outs on that occasion.

The future, more wind and solar

The Danish Energy Agency has just published its 2024 assumptions³⁰, to be used for the grid operator's planning. The document thus reflects the visions and ambitions of the Danish government and politicians.

The Energy Agency employs computer models to test the viability of the assumptions, but a lot of parameters in the models can be adjusted in order to arrive at the desired results. Denmark was until recently planning for "net zero" by 2050, but now the government has aired visions of reaching that target already by 2045 and then go for a 110% reduction target by 2050 – achieved through various methods of carbon collection and sequestration.

Accordingly, Denmark is in a hurry to expand the capacity of wind turbines, primarily offshore, and solar cells. The envisaged figures for the next 12 years are shown in fig. 17. There is a tremendous increase in the capacity of the solar cells, reaching more than 27 GW in 2035. Nearly all of it is in large farms.

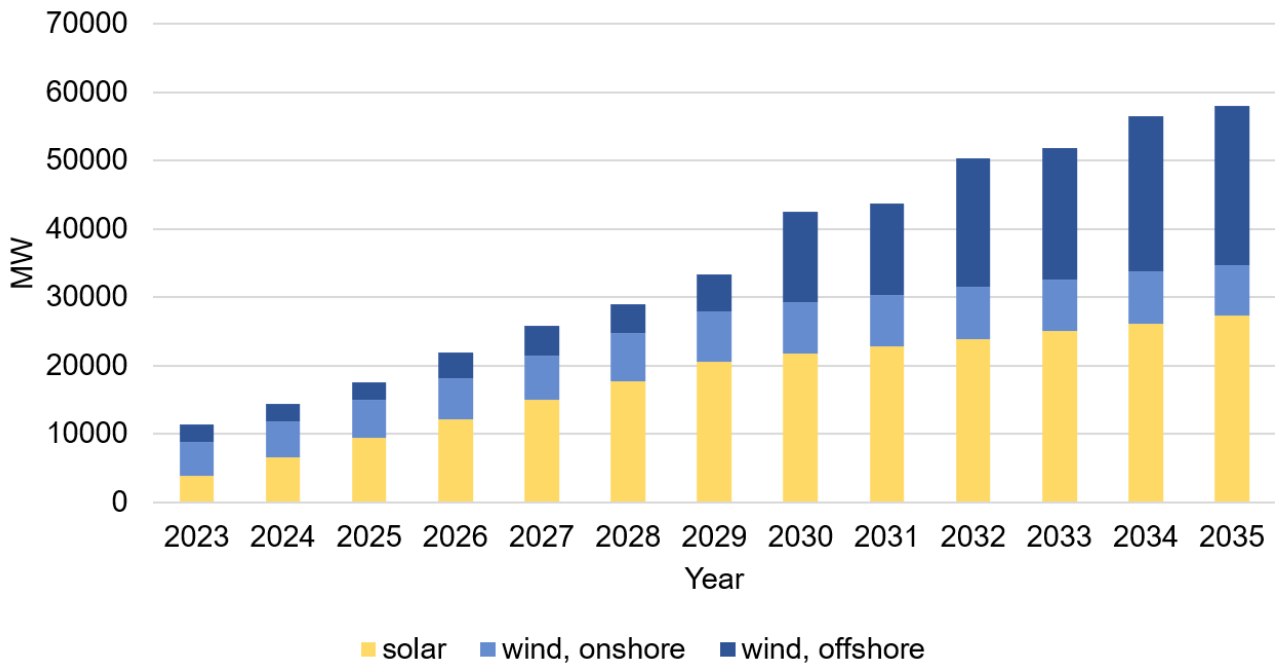


Fig. 17: The planning of the Energy Agency for expansion of solar and wind in Denmark for the period 2024-2035, in MW of capacity. Data from the Energy Agency³¹

The capacity of wind turbines on land essentially remains flat; there is a lot of local resistance to these projects, and that must have made an impression on the Agency. Offshore, on the other hand, the visions are much more ambitious, reaching a total of 23 GW in 2035, up from the present 2.6 GW.

The consumption of power for traditional purposes is not expected to grow from 2023 to 2035, however, new elements, like electric heating of houses and electrifying the transport sector (battery vehicles, etc.) will lead to an increase in power usage by a factor of around 1.4.

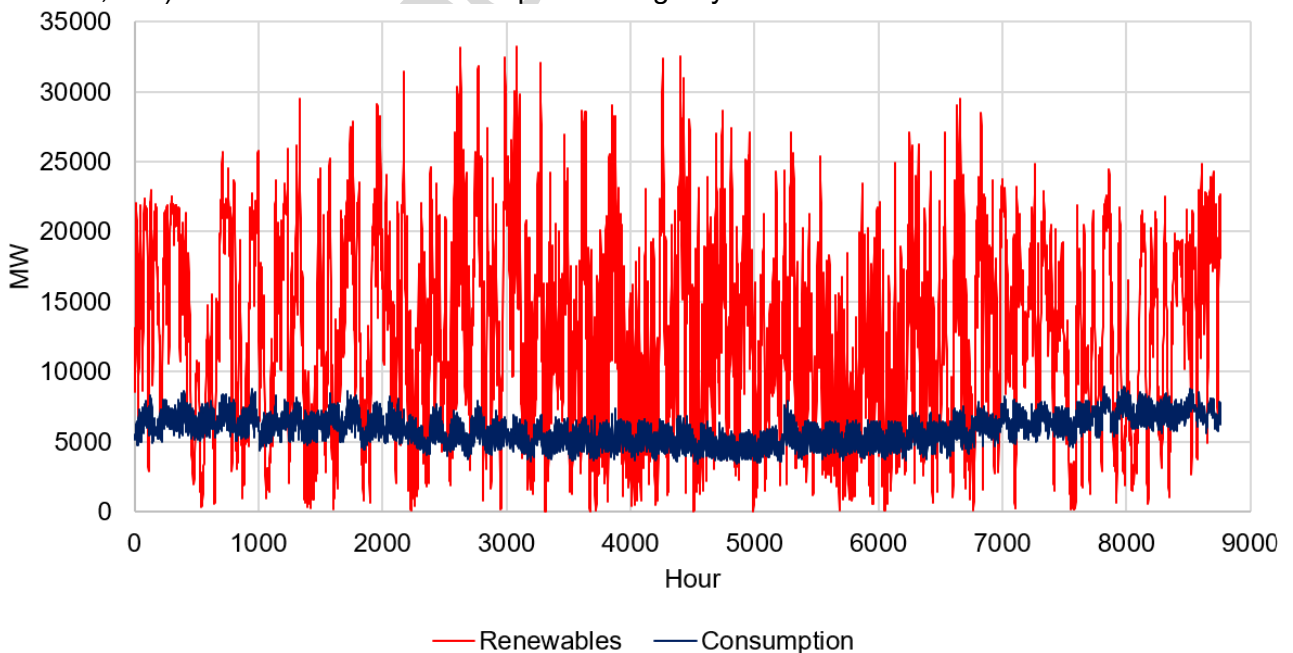


Fig. 18: Power production from renewables and expected consumption in 2035. Based on data from the Energy Agency³²

Fig. 18 shows the situation in 2035. The consumption remains within a fairly narrow band around 5000-8000 MW. The combined production from solar and wind, on the other hand is everywhere from nearly zero up to some 33,000 MW. Hence, there will be a huge imbalance between production and consumption in 2035. Of course, the total production over the year is also much larger than the total consumption.

Here, the Energy Agency brings two new consuming activities into the picture. The data centres and hydrogen production. Data centres, serving the internet companies like Google, Facebook etc., coupled with Artificial Intelligence are expected on a yearly basis to increase the consumption of power by 25% of the 2023 total. The hydrogen production would contribute with more than a doubling of the total 2023 consumption, see table 1.

Consumption, TWh	year	
	2023	2035
Traditional	36.9	52.9
Data centres	2.1	13.2
Hydrogen	0	59.2
Total	39.0	125.3

Table 1: Danish power consumption, 2023 & vision for 2035, in TWh. Data from the Energy Agency³³

From fig. 18 it is pretty clear that the power available for the data centres and hydrogen will be highly variable. Fig. 19 shows an excerpt for a few weeks in June-July. We see clearly that even with the massive expansion of wind and solar capacity, a serious deficit of power is to be expected on a number of nights. During the days, the situation is of course the opposite, huge surpluses of up to 25,000 MW.

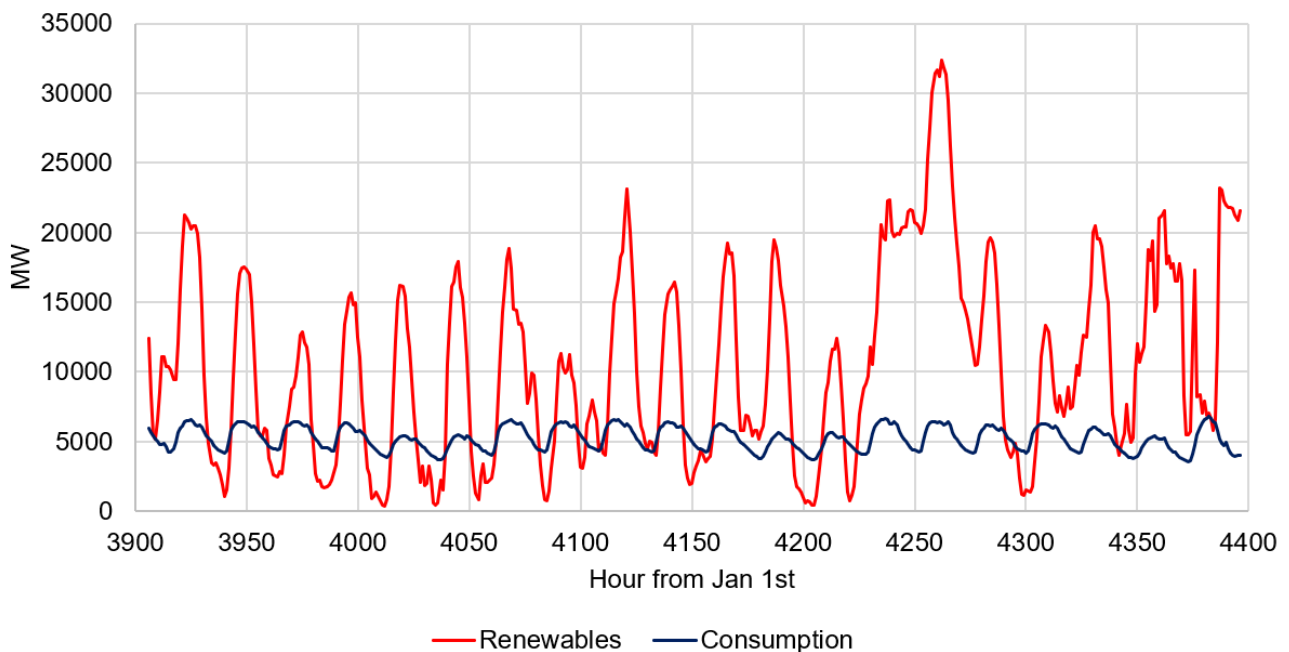


Fig. 19: Excerpt from fig. 18 covering 3 weeks in June-July, 2035.

The Energy Agency plans to reduce the total capacity of the dispatchable power plants drastically, leaving the country with less than 3 GW by 2035. Hence, the power plants will not be able to cover the shortfalls during the nights. Denmark must then rely on imports. As mentioned earlier, the power plants play a major role as suppliers of district heating. This cannot continue, and the plan is for huge centralised electric heat pumps to take over the supply for residential homes and other buildings.

The big surpluses are, as mentioned, according to the Agency to be used by the data centres, and (primarily) for hydrogen electrolysis. Whether data centres can operate on a fluctuating power supply must be regarded with some doubt. Being computer servers, they are much more likely to require a steady supply of power³⁴, for their processors, storage and cooling. If we assume that they will require an unchanging supply of power throughout the year, it will for Denmark anno 2035 be around 1500 MW and we can now calculate the power which will be available for the hydrogen production, this is done in fig. 20.

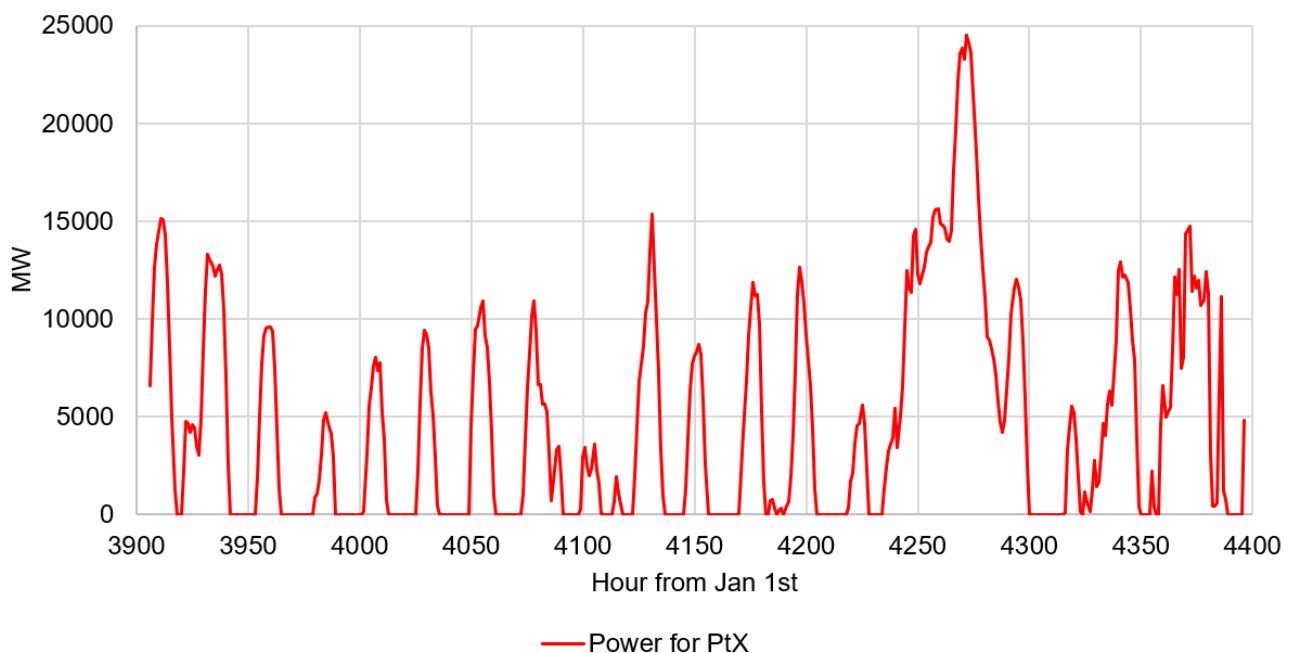


Fig. 20: Power available for hydrogen production, June-July 2035

It will obviously be a major technological challenge to establish the hydrogen production based on such fluctuating conditions, and to the writer's knowledge such a process has not been shown to work in practice. It is obvious that the run factor on the hydrogen plants will be quite low. If they have to be able to take up the maximum amount of power produced in the middle of the day, they require a huge production capacity, the main part of which will then be idle for most hours of the year. This of course will render the cost of the hydrogen much higher than what a stable production could have resulted in.

How to get there

An interesting feature, which has crept into the offshore wind business is the so-called "overplanting"³⁵. The basic idea is to install more turbines in an area than originally envisaged. If e.g. the government has set aside an area for 1 GW of turbines, the developer will be allowed to install up to 20% more capacity. The power receiving facilities ashore will still be fixed at the 1 GW,

hence in case of strong wind, some of the additional turbines will have to be stopped. But the farm will have the opportunity to deliver more power in weaker winds and also be able to compensate for turbines taken out of operation for maintenance. Overplanting will result in the turbines being placed closer to one another, and maybe closer than the optimum. However, this is the decision of the investor. In general, it can be concluded that the scheme will result in more power produced from the farm over the year, but each turbine will produce a little less on average. And the investment and other costs, of course, will be higher.

In April this year the government opened the round of bidding for the 6 GW offshore farms with the option of overplanting. The bidders for the farms are to offer how much they will pay in concessions, but whether they at all will be willing to commit to such payments is rather doubtful.

By now, apart from the economics, a further worry of the wind-farm developers is the likelihood of actually being able to sell the power they produce. The surpluses will quickly grow so big that neither the domestic market nor exports will be able to cope with the supplies. The only viable solution seems then to be the hydrogen production, which must be up and running when the turbines + all the new solar farms go on stream.

Plans are well advanced for a number of huge hydrogen plants, mainly to be built in Central and Western Jutland. However, the investors here are also reluctant, since they worry about the availability of power, but also about the market for the hydrogen.



Fig. 21: The hydrogen pipeline for exports to Germany. Image: Energinet³⁶

Denmark probably cannot use very much of the hydrogen, hence the plan is to export most of it to Germany, where the heavy industry and back-up power plants are said to thirst for the gas in the near future. But how to transport the hydrogen to Germany?

The only viable solution seems to be a pipeline going from Jutland to Germany, as shown in fig. 21. This will be costly indeed; it is estimated that the investment could be around 20 billion DKK or 2.2 billion £. The potential hydrogen producers are worried about this added cost and have requested government support. The government has now proposed to chip in 15 billion DKK, but with the condition that the suppliers pay a fee per kg of hydrogen sent through the pipe. What is worse – the government also wants the producers to guarantee that the pipe will be utilised at least by 44%.

Now, everyone is waiting for the others. The elephant in the room is of course the expected price of the hydrogen. It is rarely mentioned by the government agencies, but sober calculations indicate a cost per unit of energy which is between 4 and 8 times³⁷ the cost of natural gas. This means that e.g. German industrial buyers must think twice. Can steelworks sell their products with energy prices that much higher than what the competitors in other parts of the World have to pay? Probably not. So, is there really a market for all the hydrogen to be produced?

The hydrogen of course can serve as electricity storage, this is part of the German plans for the future of the power production. New gas-fired plants are being built, and the idea is that they are to convert to hydrogen in the 2030-s. But with the expected hydrogen prices and the enormous energy losses in the process going from electricity to hydrogen and back, the cost of the backup power will be very high, to the detriment of consumers and industry.



Fig. 22: The vision for the North Sea energy island. Image: Energiwatch.dk³⁸

The visions of the Danish Energy Agency entail a huge number of wind turbines in the North Sea and the Baltic. Bringing the power ashore from distant wind farms is very costly. Hence the idea was born some years ago of creating so-called energy islands out in the sea. In the North Sea it was to be an artificial island, mainly serving the purpose of collecting the electricity from the surrounding wind turbines, converting it to DC and then sending it ashore to Denmark, but maybe also to Germany or the UK. A proposal for such an island is shown in fig. 22.

The government has mentioned that the island also could house hydrogen production, the idea being that it is cheaper to transport hydrogen by pipeline than electricity by cable.

The cost of the island including wind turbines was estimated to exceed 200 billion DKK, (22 billion £). Cooler heads calculated the financial viability of the project, and expressed grave doubts as to the profitability. In 2023 the idea was abandoned – for now – but it is still to be found in the Energy Agency plans for the future.

As we have seen, the economy of most aspects of the energy transition does not look promising. Too many solar cells will give a surplus of power every day with sunshine, driving down prices to zero or negative figures. If this turns out to be a regular occurrence, it will seriously undermine the economy of the solar farm operators. Wind turbines and all the grid connection installations have become more expensive and with increasing interest rates, the electricity from especially offshore is no longer competitive in the present market situation. Another problem with the offshore wind turbines is the expected lifetime and maintenance costs of the equipment. Here we see very optimistic figures, 25-30 years with little cost along the way, whereas practical experience so far shows far shorter life spans and much more major maintenance required.³⁹ The turbines are installed at sea, which is considered one of the most aggressive environments for technology.

The vast quantities of hydrogen envisaged will be very costly and cannot compete with natural gas.

So, how is money raised for all these renewable projects? In Denmark we have a handful of investment companies which specialise in facilitating the process. Most notable is *Copenhagen Infrastructure Partners, CIP*, where the founders have become very rich over the last ten years or so. Their modus operandi is to plan and set up the projects, and then find investors to provide all the money. The investors will typically be pension funds or financial houses, where the awareness of the renewable pitfalls is not too great. CIP will raise the money, get the project going until completion, and then they are gone. For their effort they receive a fee from the investors, but they do not put any of their own money at risk.

Other actors in the market may initially commit to part of the investment, but after a few years of operation, they sell their shares and get out before e.g. unexpected maintenance costs kick in.

And of course, everyone in the business is looking for government support. In the end it is the ordinary people who cover the cost, as taxpayers, rate payers or pensioners.

Conclusion

The ambitious climate targets of Denmark have spurred the country far into the green energy transition. 45% of the country's energy consumption is by now covered by renewable sources. Denmark sees itself as a frontrunner in this respect, setting an example for everyone else to follow.

The country now has a combined capacity of solar cells and wind turbines exceeding the average electricity consumption by a factor of more than 2.5. This of course is far from covering all the needs for electricity, but the imbalances associated with solar and wind are already pronounced.

Sometimes Denmark has far too much electricity, sometimes too little. The main solution to this problem consists of imports and exports. Here, Denmark is very fortunate in having neighbours like Norway and Sweden who, thanks to their hydro power, are able to handle large transfers of power in either direction. Without these, Denmark would frequently find itself in serious trouble with the stability of the supply.

Now, while having a large share of solar and wind in the electricity supply makes Denmark appear to be a frontrunner, having good neighbours is not in all cases an accessible option for other countries who wish to follow the good example.

It is also a fact that two thirds of Denmark's renewable energy supply come from biomass, of which the country imports a hefty amount. Wood chips and pellets are imported for use in combined power and district heating plants. The total consumption of biomass per capita actually exceeds what globally is considered sustainable by a factor of almost 3. Again, other countries could not copy the Danish way in this respect, and hence Denmark might not be that much of a frontrunner.

Grand plans have been put on the table for a huge expansion of the solar- and wind-based energy production in Denmark, but there is no realistic solution on the table regarding how to handle the enormous fluctuations in the ensuing energy supply. The main solution seems to be hydrogen production, which miraculously is expected to work on a highly variable power input.

The economy of the entire energy scheme seems increasingly doubtful, the power costs fluctuate enormously and the hydrogen that might be produced will be very expensive, basically rendering any usage wildly uncompetitive with e.g. natural gas.

Denmark is with the climate policies looking into huge costs, an unstable energy supply and most likely a financial downturn within a few years. This will make the country a frontrunner, but is it in a direction any other sensible government would like to follow? I think not.

Note on the author

Søren Hansen is a chemical engineer, M.Sc., now retired after a long career in the chemical industry. He is currently the editor and chief contributor to the Danish-language website *Klimarealisme.dk*, which is the only climate-sceptic web page in Denmark. Søren Hansen is the author of 3 books concerning the climate, all in Danish: "*Klimaplan 2030 – Realisme eller Utopi*", "*En grøn drøm*" (a novel) and "*Troen på klimaet*".

References

- ¹ https://ens.dk/sites/ens.dk/files/Statistik/foreloebige_energistatistik_2023.xlsx
- ² <https://turbines.dk/statistics/#time>
- ³ <https://ens.dk/ansvarsomraader/vindmoeller-paa-hav/etablerede-havvindmoelleparker>
- ⁴ <https://ens.dk/ansvarsomraader/vindmoeller-paa-hav/etablerede-havvindmoelleparker>
- ⁵ <https://vejr.tv2.dk/2023-11-01-en-type-energi-er-naermest-eksploderet-i-vaekst>
- ⁶ <https://www.energidataservice.dk/buildreport>
- ⁷ Kraka Advisory: "Energigøen i Nordsøen – proces fakta og risici", report 2021
- ⁸ Gordon Hughes: "Wind Power Economics Rhetoric & Reality", Vol. 2, Edinburgh 2020
- ⁹ <https://ens.dk/presse/thor-wind-farm-skal-bygge-thor-havvindmoellepark-efter-historisk-lav-budpris>
- ¹⁰ https://www.energy-supply.dk/article/view/1018720/aben_dorstop
- ¹¹ https://www.energy-supply.dk/article/view/877983/analytiker_om_nedjustering_hos_vestas
- ¹² <https://renews.biz/87865/four-ny-offshore-projects-ask-for-almost-50-price-rise>

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- ¹³ <https://energinet.dk/el/elmarkedet/modhandel/>
- ¹⁴ <https://via.ritzau.dk/pressemeddelelse/13771855/slut-med-stoppede-vindmoller-i-blaesevejr?publisherId=10304728&lang=da>
- ¹⁵ <https://www.energidataservice.dk/buildreport>
- ¹⁶ <https://www.technologyreview.com/2021/07/14/1028461/solar-value-deflation-california-climate-change/>
- ¹⁷ <https://www.energidataservice.dk/buildreport>
- ¹⁸ Ibid.
- ¹⁹ <https://energinet.dk/Om-nyheder/Nyheder/2022/03/18/Drivende-skyer-sluger-alle-Energинets-reserver-til-at-sikre-balancen-i-elsystemet/>
- ²⁰ <https://kefm.dk/aktuelt/nyheder/2022/okt/regeringen-vil-udskyde-lukning-af-tre-kraftvaerker->
- ²¹ <https://www.dst.dk/da/Statistik/nyheder-analyser-publ/nyt/NytHtml?cid=46139>
- ²² <https://ens.dk/service/statistik-data-noegletal-og-kort/maanedlig-og-aarlig-energistatistik>
- ²³ <https://www.eestimetsaabiks.ee/eng/>
- ²⁴ IPCC Special Report: "Global Warming of 1.5 °C", <https://www.ipcc.ch/sr15/>
- ²⁵ <https://www.energidataservice.dk/buildreport>
- ²⁶ http://www.pfbach.dk/firma_pfb/monthly_dk_prod_2023.htm
- ²⁷ https://www.researchgate.net/figure/Nord-Pool-Spot-price-areas_fig5_344025387
- ²⁸ <https://energinet.dk/om-publikationer/publikationer/arsmagasin-2023/>
- ²⁹ <https://www.tn.se/naringsliv/32092/sa-sprider-sig-tysk-elkris-till-grannlanderna-danmark-ropar-pa-hjalp/>
- ³⁰ <https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsætninger-til-energinet>
- ³¹ Ibid.
- ³² Ibid.
- ³³ Ibid.
- ³⁴ <https://dgtlinfra.com/data-center-power/>
- ³⁵ https://ens.dk/sites/ens.dk/files/Energioer/2-supplerende_hoering_til_foerste_offentlighedsfase_af_miljoevurdering_af_planen_for_program_energieoer_bornholm_notat_om_overplanting.pdf
- ³⁶ <https://energinet.dk/om-nyheder/nyheder/2023/06/22/dansk-brintsystem-kan-give-milliardstorsamfundsgevinst/>
- ³⁷ <https://www.gov.uk/government/publications/hydrogen-production-business-model-net-zero-hydrogen-fund-shortlisted-projects>
- ³⁸ <https://energiwatch.dk/Energinyt/Renewables/article14524538.ece>
- ³⁹ Gordon Hughes: op. cit.