Technical University of Denmark

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Integrated Energy Grids - 46770

Course project: Analyzing the Danish system in 2030

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1 Model setup, parameters and assumptions (*Task A*)

1.1 Model setup

In this project, it is chosen to model the energy(mainly electricity) system in Denmark, which is modeled as one node in the energy system optimization model PyPSA. Denmark's electricity market is divided into two regions, namely DK1 and DK2. However, it is chosen to only model Denmark as one node since the objective is to look at the bigger picture and not regional differences in Denmark. Later, the model will be extended with interconnection links to other countries such as Germany. The year that will be analysed in terms of cost is 2030. For the demand, the year 2019 is multiplied by 1.55, simulating the consumption in 2030 which is expected to be 55% higher than today[1]. Later in the assignment, the weather years will also be varied, but as a default and for the following plots, the weather year is chosen as 2017.

1.2 Parameters and data

To run the model, data specifying technology cost, electricity generation of technologies, weather data, and demand are all needed. Demand data is gathered from the Open Power System Data initiative [2], which provides hourly data for the demand for several years. For the weather profiles, the data is gathered from the Zenodo database in [3] & [4]. The various technology costs are from the PyPSA cost database [5]. However, for the VOM cost of offshore and onshore wind, the newest Danish technology catalog is used [6].
It was considered to constrain land buildout of solar PV and onshore wind, but decided to let the model decide freely. This means that all generation technologies are unconstrained.

1.3 Electricity generation mix

The model is optimizing the system and is finding the following generation mix in Figure 1. Where the model finds nearly 60% variable renewable energy generation in the system (VRE) and the rest as gas. This is close to the current capacity mix of VRE in Denmark, which is also around 60% [7]. It is seen that wind is the dominant VRE opposed to solar which is also the real case, however solar PV is slightly higher. This might be explained by the usage of the specific weather data of 2017. This will be analyzed later in section 3.

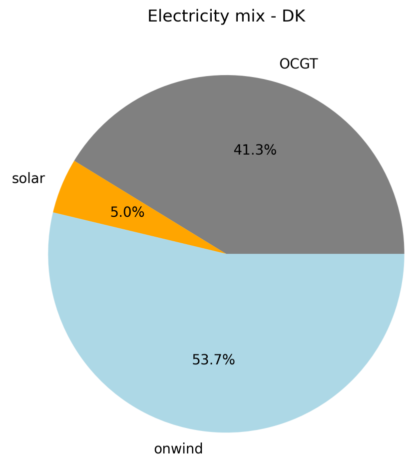


Fig. 1: Electricity generation mix in Denmark in 2030

The specific capacity values of the technologies are shown in Table 1.

Tab. 1: Optimized Generator Capacities - DK

	OCGT	solar	onwind	offwind
Optimized Capacity (MW)	8218	994	10696	0

1.4 Duration curves

Duration curves are created using the wind and solar resource data along with the optimized dispatch result for the OCGT gas power plant in Figure 2. The duration curve for offshore wind is also shown, even though it is not part of the initial system. The curves show that offshore wind has an almost linear curve and is always producing more than onshore wind since the wind resource is better and more stable at the ocean. However, it is noticeable that both wind generation is almost never at 0. The solar curve shows that it only operates half of the year and at very varying capacities, as expected from the daily and yearly solar irradiation patterns. Lastly, the gas powerplant can be seen operating quite often at around half capacity and is actually only completely off for a few hours.

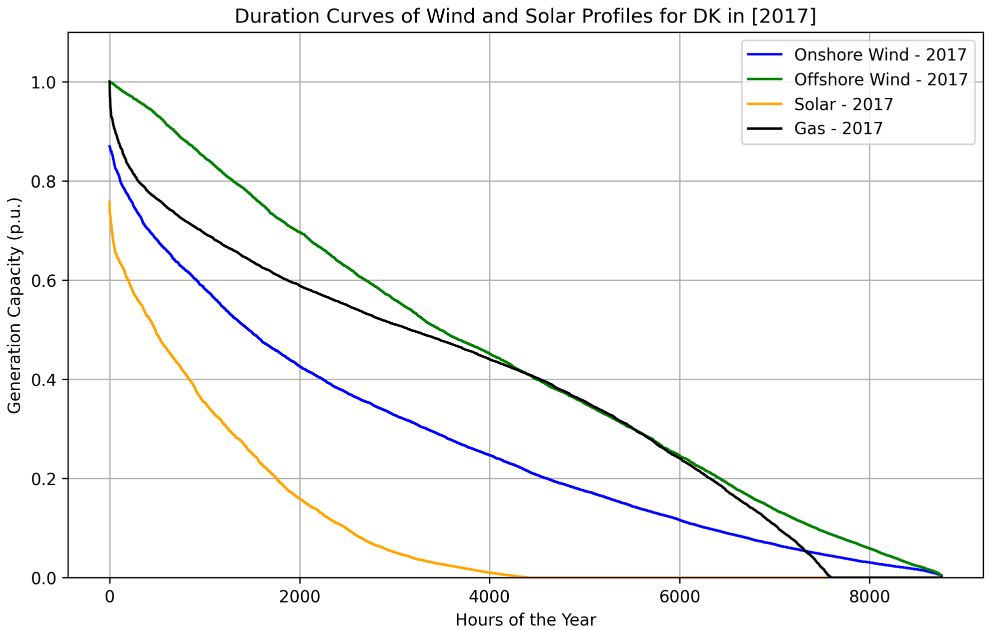
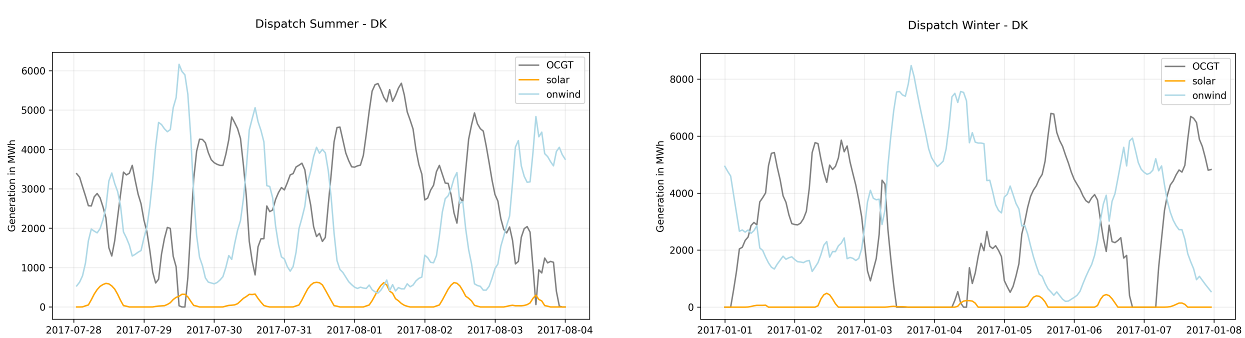


Fig. 2: Duration curve for electricity generation in Denmark in 2030

1.5 Generation dispatch summer and winter

In Figure 3, the operation of the different generation technologies is shown for a random week during summer and winter. In general, it can be observed that the gas generator is used to balance the system when the VRE production is low. As the installed solar capacity is a lot lower than the onshore wind, it is mainly balancing the wind. Comparing summer and winter, we see that production is higher during winter, which is primarily due to higher demand for electric heating and lighting. As expected, solar production is a bit lower in the winter.



(a) Operation dispatch Denmark in the summer

(b) Operation dispatch Denmark in the winter

Fig. 3: Comparison of operational dispatch in Denmark for summer and winter

2 Global carbondioxide constraint (*Task B*)

The generation mix is plotted as a function of the imposed global CO2 constraint. In Denmark, there is a climate law[8] stating that DK should reduce its greenhouse gas emissions by 70% compared to the 1990 level in the year 2030. However, DK has a lot of agricultural GHG emissions and thus the allowance for the electricity sector is even lower and is projected at 0.1 Mton CO2e in 2030. What is seen in **??** is that the generation mix changes dramatically as the allowance is tightened. Another interesting observation is that offshore wind (OffW) is penetrating the system as the limitation is lower, and that is pushing out onshore wind(OnW), except in the last case. The interpretation could be that the production from OffW is higher than OnW during low resource hours (as seen in the duration curves 2) and these are specifically the crucial hours when the CO2 constaint is limiting the OCGT generation. The presence of OffW then overshades the need for OnW. It is also seen that the solar is increasing. Presumably, since some of the peak demand hours with low wind are during the day when solar is available. For a 0.1M CO2e allowance, the system goes crazy, which is likely due to the presence of a few hours with low wind and solar that the OCGT cannot cover because of the constraint. This increases the installed VRE a lot to cover those hours and have the solution feasible. The comeback of OnW entails that the onshore wind production is higher than the offshore in some of the critical hours. This case is very unrealistic, and will be different if you allow energy storage, demand flexibility, or other flexible renewable generators like a biomass CHP plant.

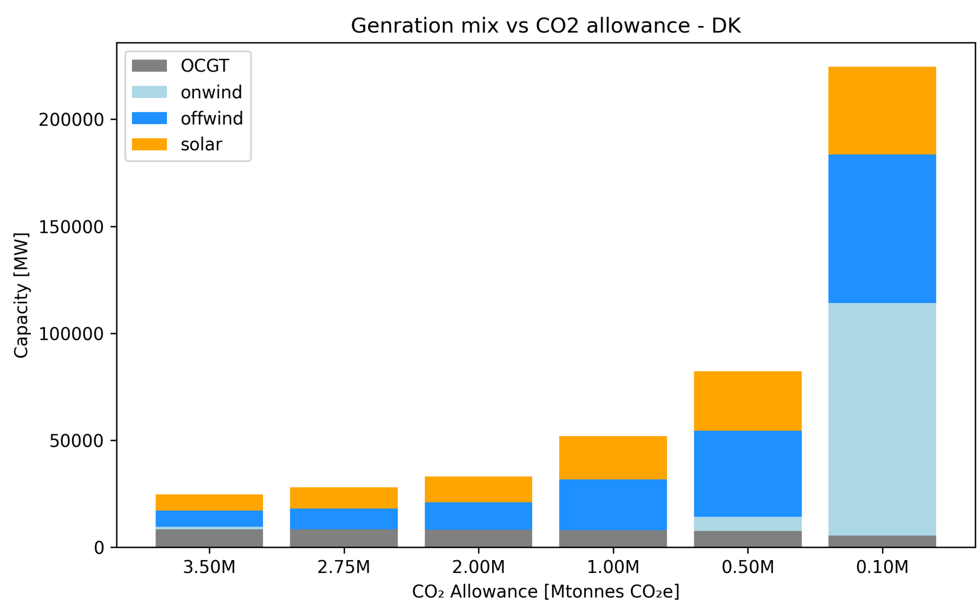


Fig. 4: Electricity mix as a function of CO2 allowance

3 Inter-annual weather variability (*Task C*)

As shown in Figure 5, the generation mix varies noticeably across the years 2012–2017, reflecting the impact of inter-annual weather variability on system design. While the overall distribution between technologies remains relatively stable, the capacities of individual technologies fluctuate in response to changes in wind and solar resource availability.

Onshore wind shows both upward and downward deviations from the baseline year (2017), with notable increases in 2014 and 2015 and a marked dip in 2016, likely due to weaker wind conditions in that year. Offshore wind, on the other hand, appears more selectively utilized, with a capacity increase occurring only in 2016, suggesting a targeted deployment to compensate for onshore variability. The solar capacity demonstrates the highest relative volatility, with significant expansions in years with strong solar potential (2013 and 2016), and minimal investment in less favorable years such as 2017.

OCGT (Open Cycle Gas Turbines) is used as a flexible backup technology, with its capacity shifting to balance the variability in renewable output. It tends to increase in years with weaker renewable resources, which highlights its role as a dispatchable buffer against weather-driven fluctuations.

The average column summarizes the long-term investment trend, illustrating how the system might be dimensioned if one were to plan based on a multi-year average rather than a single year. Comparing the average against individual years highlights the potential risk of over- or under-investment when relying on weather data from a single year.

This analysis underscores the importance of incorporating interannual variability into energy system planning. Designs based on a single year risk either oversizing dispatchable capacity or underutilize renewable potential. Thus, robust system design should evaluate performance across multiple weather years to ensure resilience and cost-effectiveness.

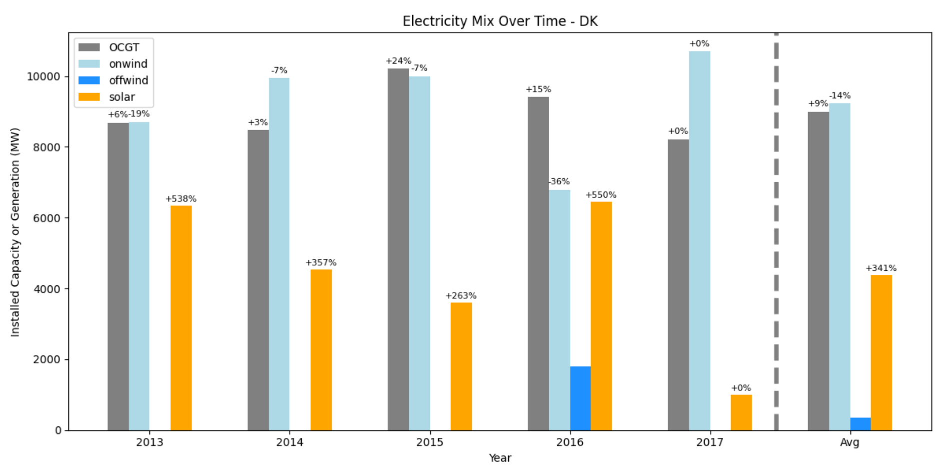


Fig. 5: Installed capacity of generation using variable annual weather data

4 Storage integration (*Task D*)

Figure 6 illustrates the dispatch profile and state of charge (SOC) of storage technologies for the DK region. The system includes two types of storage: lithium-ion battery storage and a hydrogen (H_2) storage tank. Their operation sheds light on the strategies used to balance renewable generation across different timescales. Battery storage is actively engaged throughout the simulation period, with distinct intraday charge and discharge cycles. This reflects its role in short term balancing, where it absorbs surplus generation typically during midday solar peaks or high wind periods and discharges during evening demand peaks or low renewable intervals. The sharp fluctuations in SOC further support this fast response function.

In contrast, the H_2 storage tank remains entirely inactive over the simulated year, with a flat SOC profile. This suggests that, under current cost and system assumptions, the model does not find it economically optimal to utilize hydrogen for electricity shifting.

The system's balancing strategy is clearly scale dependent. On an intraday level, batteries handle fast fluctuations efficiently. Over multi-day periods, the combination of wind diversity and dispatchable open-cycle gas turbines (OCGT) maintains supply-demand balance. However, no seasonal balancing is evident in this configuration. The model simply does not find it cost effective to include hydrogen storage for long-term energy shifting under the current assumptions. As a result, dispatchable thermal generation continues to play a crucial role in maintaining system balance. Especially when observing periods of low availability of renewables.

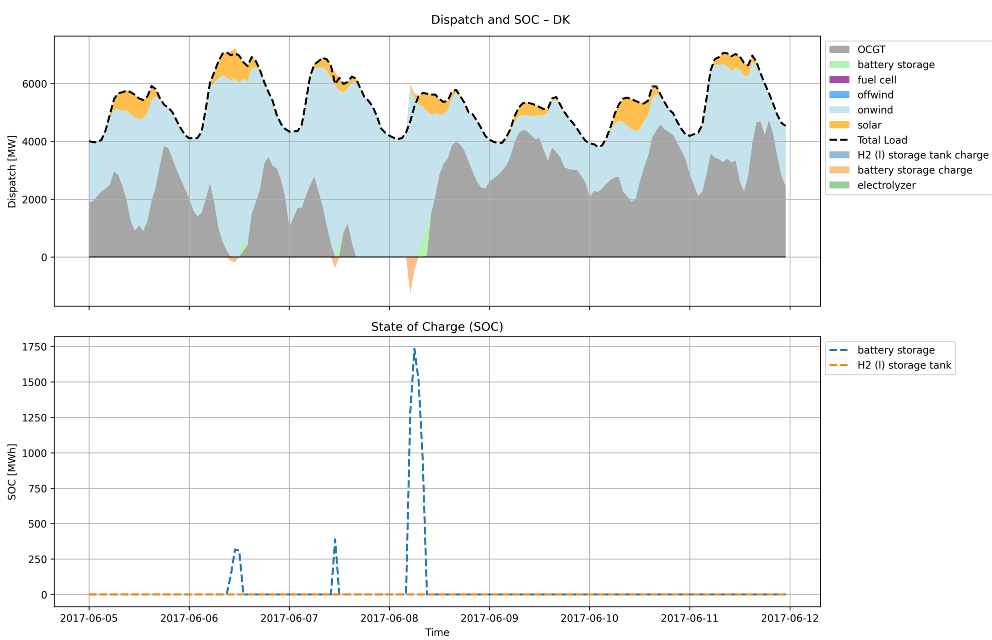


Fig. 6: Dispatch and state of charge for battery and H_2 storage in DK

5 CO2 Price (*Task E*)

The CO2 price is investigated through the various CO2 allowances investigated in section 2. This yields the results shown in the table below:

Tab. 2: CO2 Price as a Function of CO2 Limit

CO2 Limit [tCO2]	CO2 Price [€/tCO2e]
3 500 000	116.7
2 750 000	203.9
2 000 000	358.3
1 000 000	785.7
500 000	1561.6
100 000	5023.2

Since the system here does not include all the technologies that it otherwise would, such as biogas and biomass CHP plants, it has a very high CO2 price since the model's solution is to install a lot more capacity of the VRE as was also seen in Figure 4. However, it is seen that with an emission allowence of 3.5 Mton CO2e it is not too far from the current prices of around 80 [€/tCO2e]. The electricity sector did have an emission in DK of 3.127 Mton CO2e in 2030 [9]. However, instead of imposing these prices on the model, the forecasted European CO2 price in 2030 at 150 [€/tCO2e] is used [10].
This gives a new electricity mix, seen in Figure 7 which includes only offshore wind instead of onshore wind and a lot more solar and less gas. The increase in solar is also due to the inclusion of battery storage.

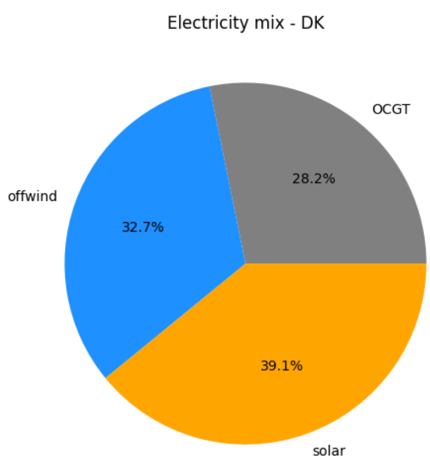


Fig. 7: Electricity generation mix in Denmark in 2030

For the following sections the 150 [€/tCO2e] price will be used.

6 Connection to other countries (*Task F*)

Denmark is then connected to Germany and Norway. This is done by HVAC cable between Denmark and Germany with an efficiency of 95%, and a HVDC submarine cable between Denmark and Norway with an efficiency of 99%. The electricity consumption of Germany and Norway is similarly to Denmark scaled such that it fits according to 2030. For Germany this results in an increase of 11% consumption in year 2030 [11], and 21% increase in year 2030 [12] for Norway. With these adjustments the electricity demand of the countries can be written as:

Tab. 3: Optimized Generator Capacities - DK

	Denmark	Germany	Norway
Annual Electricity load (TWh)	51.98	544.42	159.39

The countries have the same technologies available, with the addition of Norway also having a hydro storage facility. The data for this facility has been given during the course. Upon simulation of the system it was noted, that when no upper bound for the transmission line capacity were chosen, Denmark would have an electricity mix of 100% onshore wind, and Norway would also transport the renewable energy generation through Denmark to Germany. As this was deemed unrealistic a transmission capacity of the HVDC between Denmark and Norway was chosen to be 1,700MW, and the connection between Denmark and Germany was chosen to be 2,500MW. With these limitations the maximum capacity of the transmission lines were the optimal solution, with an electricity mix of Denmark consisting of:

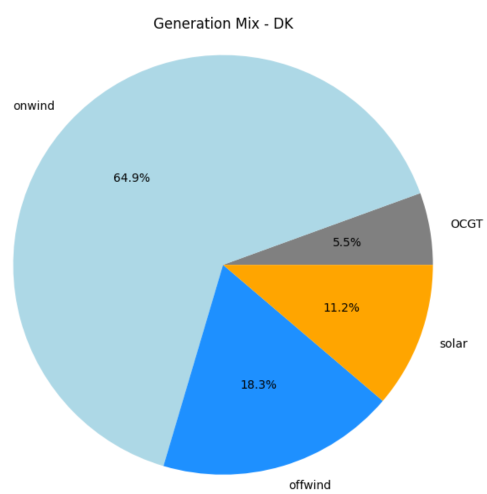


Fig. 8: Electricity generation mix in Denmark with international transmission

With the introduction of international transmission connections, the annual electricity mix of Denmark installs onshore wind to supply the German demand. This is done to lower the cost enforced by the carbon tax.

7 Connection with another sector (*Task G*)

The model is then connected with the heating sector, by introducing heat demand busses. The annual heat demand in each of the countries is given by:

Tab. 4: Optimized Generator Capacities - DK

	Denmark	Germany	Norway
Annual Electricity load (TWh)	51.98	544.42	159.39
Annual Heat load (TWh)	53.69	817.37	68.52

To supply the heat demand industrial high temperature heat pumps are introduced along with heat recovery from the electrolyzers. For a week in January the electricity dispatch is plotted along with storage state of charge and heat dispatch:

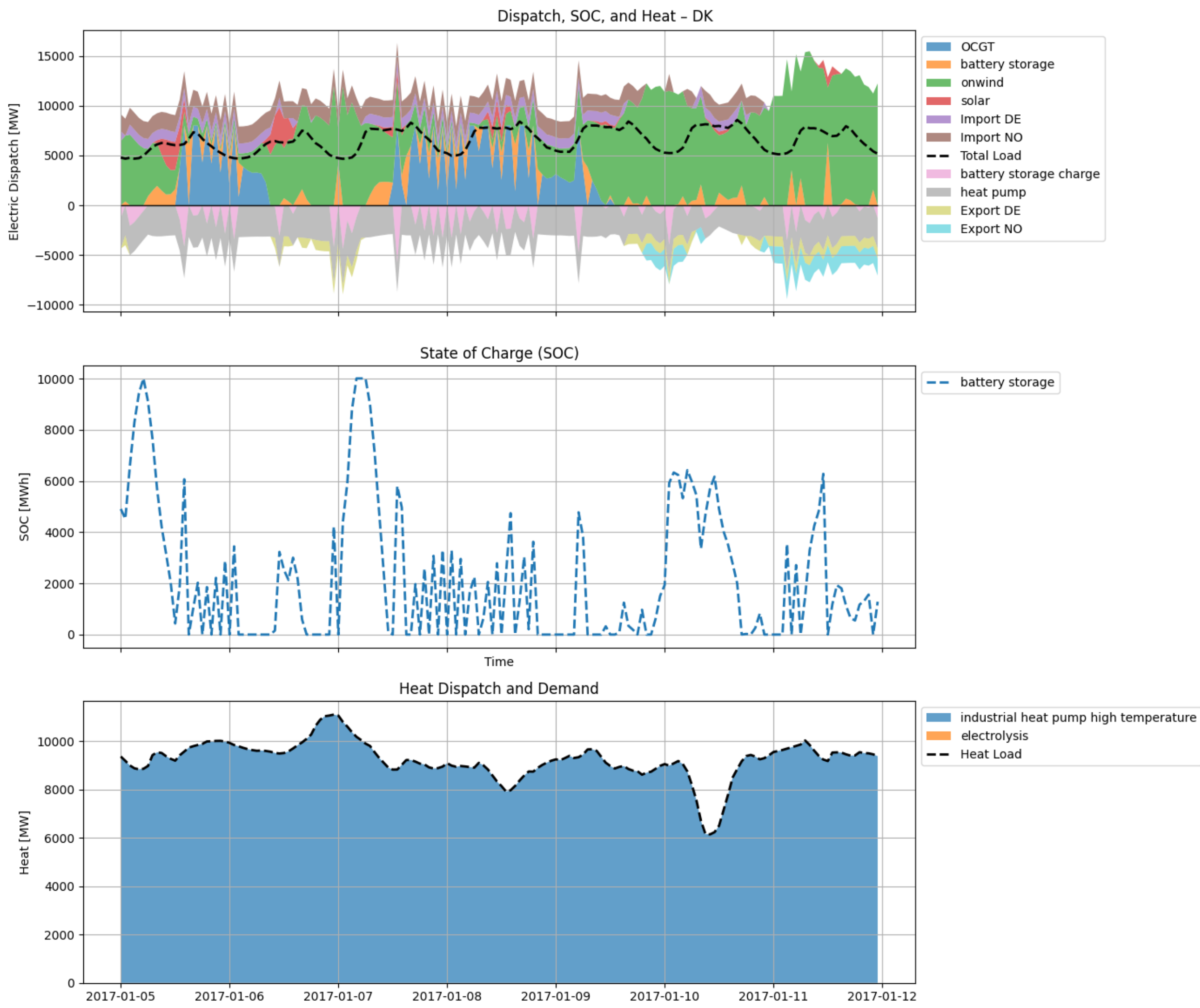


Fig. 9: Electricity and Heat Dispatch with battery State of Charge

Even with the possibility of using the recovery heat of the electrolyzer it is not optimal to invest in hydrogen technologies. From this plot it is also visible how the high onshore wind power generation is distributed to the neighboring countries, and that the battery is utilized to avoid the usage of the gas turbine.

8 Hydrogen Backbone Integration Between DK and DE (*Task H*)

8.1 Motivation

As Denmark moves toward a fully decarbonized energy system, hydrogen is receiving growing attention as a flexible energy carrier [13]. It can be used both for long-term energy storage and to link the electricity sector with other sectors such as industry and heavy transport. With its strong wind resources, Denmark has the potential to produce large amounts of green hydrogen through electrolysis which besides domestic usage, could also be exported to neighboring countries with higher demand [14].

This idea fits the European Hydrogen Backbone (EHB) initiative, which aims to build a network of hydrogen pipelines connecting resource-rich areas like the Nordics to major demand hubs like Germany [13]. In Denmark, Energinet has studied the possibility of a hydrogen pipeline to Germany. [15].

To explore this in a simplified way, the PyPSA model is extended to include a hydrogen pipeline between Denmark and Germany with a capacity of 1 GW. The goal is to investigate how even a partial implementation of such a hydrogen link could influence system design and energy flows.

8.2 Results

When we ran the model, it did not use the link at all, even if we gave it for free. This corresponds to the low efficiency of converting the electricity to hydrogen and back to electricity again, along with the high cost of electrolyzers and fuel cells. What should have been done is to include a hydrogen demand simulating the demand from PtX production. Additionally, the heating sector could have been directly integrated with hydrogen, as some of the heating demand could be covered by burning hydrogen, which we know could be the case especially in Germany's heavy industry sector. Furthermore if, had the heavy transport sector been included along with different PtX technologies been included we would expect hydrogen demand to have increased even further. These are generally the motivating factors for having the hydrogen backbone from DK to DE.

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