Modelling the Future Energy System of Germany

Benjamin Simonsen | 201507247

A Project in Renewable Energy Systems

Department of Mechanical and Production Engineering
Aarhus University
Denmark

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1 Introduction

During this course, we have been studying the design of renewable energy systems, with particular focus on the European electricity network. The purpose of this project is to implement the tools attained throughout the course in an optimisation model and analyse the results. Specifically, I will be using PyPSA (Python for Power Systems Analysis) to simulate and analyse the energy system of Germany.

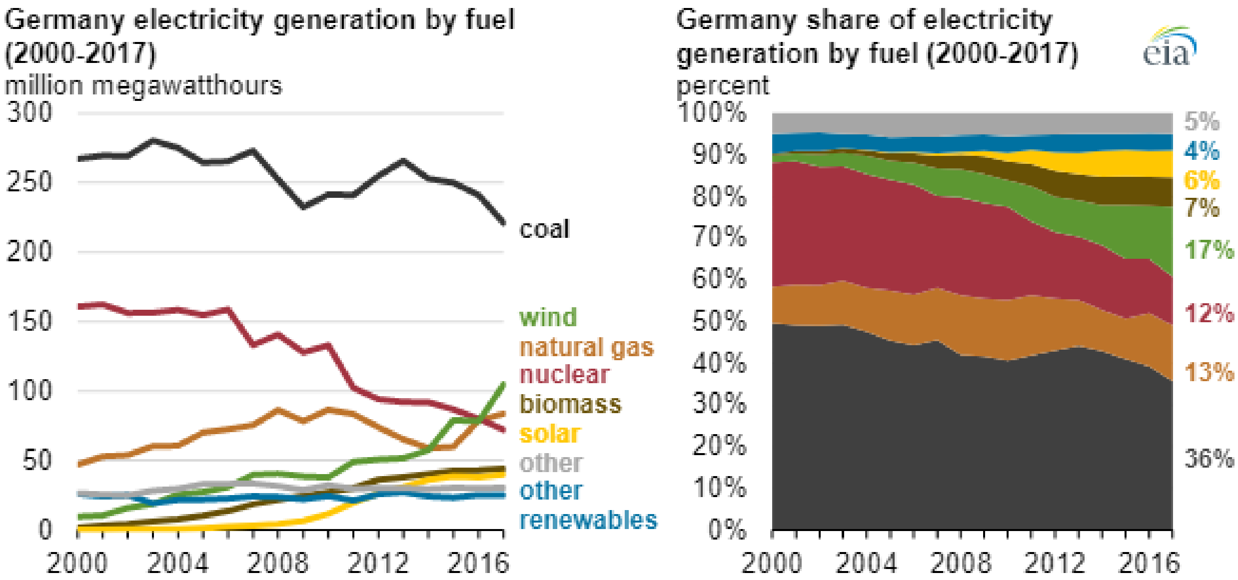


Figure 1: *German Electricity mix since 2000. Source: U.S. Energy Information Administration, based on German Association of Energy and Water Industries [**5**].*

Germany is an interesting case to investigate as it already includes relatively large proportions of renewables in its power production (17% wind, 7% biomass, 6% solar, 4% other, mainly hydro as of 2017) and yet still has aggressive targets to expand in the near future[**16**]. 12% of the nations electricity comes from its 4 remaining nuclear power plants, all of which will close on or before December 31st 2022. In addition, the government have proposed plans to phase out the country's primary fuel, coal, by 2038 [**5**], leaving a huge gap for cleaner and greener technologies to fill. Taking these goals into consideration, I will try to model what such a future energy system might look like in Germany; one without nuclear or coal power plants. In the following sections, I will provide a brief description of the model itself and then proceed to analyse its outputs to test how such a system functions.

2 The PyPSA Model

The power production technologies included were onshore and offshore wind turbines, solar photovoltaics, open cycle gas turbines (OCGT), coal and nuclear power plants (with maximum install capacities set to zero for Germany). The storage technologies included were pumped hydro storage (PHS), hydrogen storage (H2) and batteries. All cost assumptions, limits imposed, and efficiencies are given in table 1 below. Solar power is assumed to be a 50/50 split of rooftop and utility scale, while hydro power is taken to be fully built and paid for in the past and not expandable beyond what is installed today (about 11GW [**6**]), hence only operation and maintenance (O&M) costs are considered. The discount rate was assumed to be 7% for every technology, except for solar power, for which it was taken to be 5.5%.

The model uses hourly resolution data of the electricity demand of Germany provided by [**2**], and hourly resolution

	build cost[€/kW]	O&M [%/year]*	lifetime[y]	η [%]	capacity$_{max}$[GW]	ref.
onshore wind	910	$3.3 + 1.5€/MWh$[10]	30	100	57.7	[10]
solar**	575	2.5	25	100	-	
gas (OCGT)	560	3.3 + 21.6€/MWth	25	39	-	
coal	1900[12]	3.3[12] $+ 11.25€/MWth$[10]	25[12]	40[12]	0	[10][12]
nuclear	3700	3.3 + 11.5€/MWth	30	39	0	[9]
offshore wind	1930	$3 + 3€/MWh$[10]	25	100	115.4	[10]
hydro***	0	1	80	75.69	11	
H2 tank	8.4	0	20	-	-	
H2 electrolysis	350	4	18	80	-	
H2 fuel cell	339	3	20	58	-	
batteries	144.6	1	15	-	-	
battery inverter	310	3	20	90	-	
HVDC link	190	2	40	100	14.4	

Table 1: *Assumptions made in the optimisation for each technology. Unless another source is given in the rightmost column, all assumptions come from* [**1**]*. The discount rate was assumed to be 7%.*
* *the fixed O&M costs are in percent of build cost per year. Marginal cost is given for some generators and zero for others.*
** *solar is assumed to be a 50/50 split of rooftop and utility scale with a discount rate of 5.5%*
*** *hydro efficiency is assumed to be fully built an not expandable beyond what is installed today. PHS efficiency is 0.87 in and 0.87 out.*

weather data given by [**3**] and [**4**] to predict the availability of wind and solar resources in every time step. Unless otherwise stated, the data used will be from 00:00 January 1 - 23:00 December 31 2015. The model also includes daily inflow data for hydro power available here [**7**], although this will be from the year 2012.

Limits are imposed on some technologies, for example, the total capacity of onshore wind energy that can be installed in the system. Given that wind farms require a lot of space and are disturbing to local populations, it seems reasonable that onshore wind can not be indefinitely expanded. Further justification of the limits on install capacities and link capacities will be found in section 3.3.

The model includes the ability to add constraints such as a cap on total carbon emissions allowed. The cap will be adjusted based on percentage reduction as compared to emissions at 1990 levels (381Mt) [**8**].

In sections 3.3, other countries will be added with the same technologies and with the same cost assumptions as given in table 1. The countries will be connected using high voltage direct current (HVDC) links. In Section 3.4 Heating demand will be included, which can be found here [**7**].

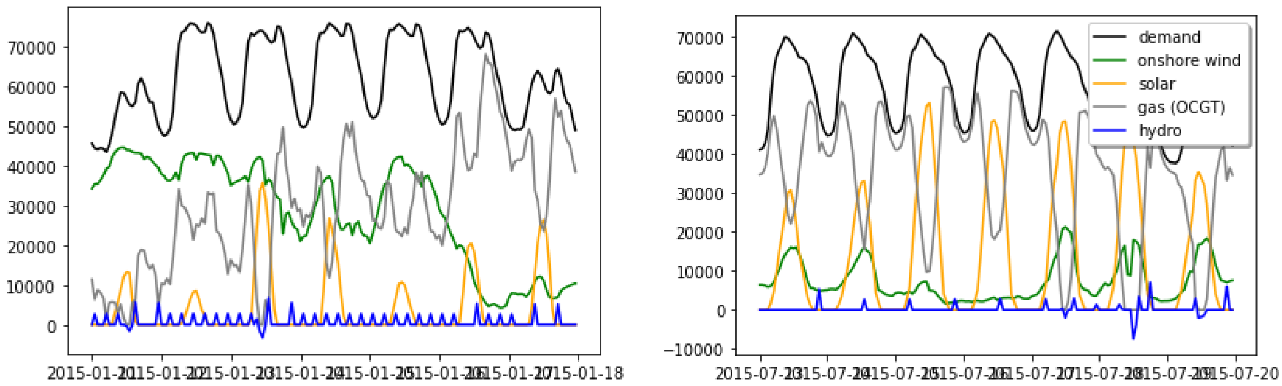
3 Results

3.1 Isolated System

First, let's have a look at the optimal system configuration. Figure 2 below shows the electricity dispatch during one week of winter and one week of summer. A pie-chart of the electricity mix and the capacity factors for each technology included in the system is also found below in figure 3a and table 2. Technologies not shown were not chosen by the optimiser.

Figure 2 shows characteristically higher wind energy levels and hydro inflow during winter, with higher levels of solar energy being produced in the summer. With no carbon limit set, the system used gas power as backup to meet the demand.

The capacity factors for the two primary renewable sources (table 2) is 20.5% for onshore wind and 11.7% for



(a) *Dispatch during a week in winter in MWh*

(b) *Dispatch during a week in Summer in MWh*

Figure 2: *Dispatch during one week of winter and one week of summer, the system is isolated. Higher wind levels and hydro inflow during winter, with higher levels of solar energy in summer. With no carbon limit set, the system only uses gas power as backup*

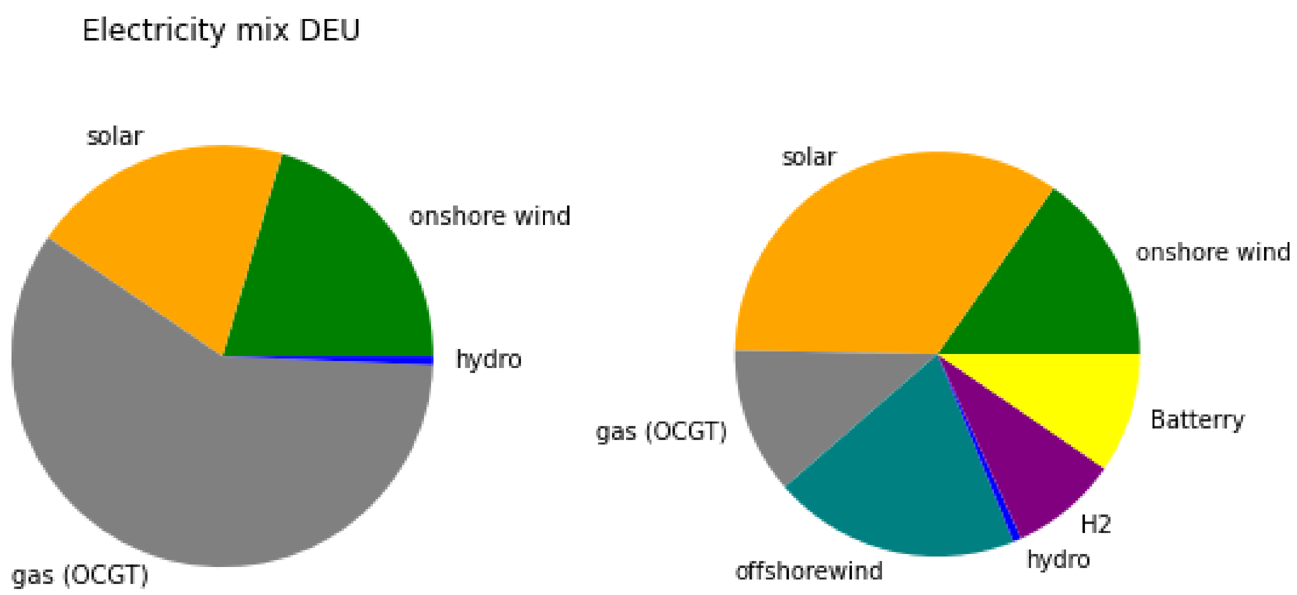
	Install Capacity [GW]	Capacity factor [%]	Energy Dispatched [TWh]	Share of Total [%]
Onshore Wind	57.7	20.5	103.5	20.4
Solar	98.9	11.7	101.5	20.0
Gas	70.4	48.4	298.2	58.9
Hydro	11	3.5	3.3	0.7

Table 2: *Optimal German energy system configuration with no carbon cap, isolated*

solar. Were this system to be built, these capacity factors would naturally change depending on the weather. A particularly windy year would yield a higher capacity factor for wind energy and likewise with sunnier years for solar. Figure 4 shows the capacity factors for the years 2008-2015 for wind and solar (although no offshore is installed in the isolated system, it will come into play in later sections and is included in the figure). The capacity factors for solar lie roughly in the range 11-12%, while for wind energy the ranges are 19-22% for onshore and 30-35% for offshore. The figure includes the standard deviations of the hourly capacity factors of each energy source, a measure of how varied the hourly energy production is from the yearly average. These show that although offshore wind has higher average capacity factors, the hour to hour energy is also more spread out around that average. This is not an advantage in an industry that values control and predictability. It is also evident that years with higher average capacity factors have higher variability, this is true of all three technologies.

3.2 Carbon Cap

Even with no carbon limit imposed, the optimal system results in a reduction of 61.9% compared to 1990's levels. This is not because the demand has decreased since 1990, rather it is because the energy system of 1990 was powered by over 50% coal which emits more CO_2/MWh [**11**]. We will now see how the system changes as we adjust the carbon cap. First the system is optimized with a limit on emissions corresponding to a 60% reduction (yielding no changes), then the cap will be lowered until there is no carbon emissions allowed. The changes in system components as the carbon cap is lowered can be seen in figure 5, as well as the corresponding price of carbon needed to make the limit possible in the market, and the price of electricity. A pie-chart of the electricity mix obtained with carbon cap set to 90% reduction can be seen in 3b. At 90% reduction, the cost of electricity is 71.7€/MWh, the carbon price would need to be 166.4€/ton, and because some power is dispatched, stored, and later dispatched again, the total energy dispatched is 135% of the total demand. The full system components can be found in table 3. The limit of total carbon emissions to 10% of Germany's 1990 emission levels will be present in all optimisations discussed from here on.



(a) (b)

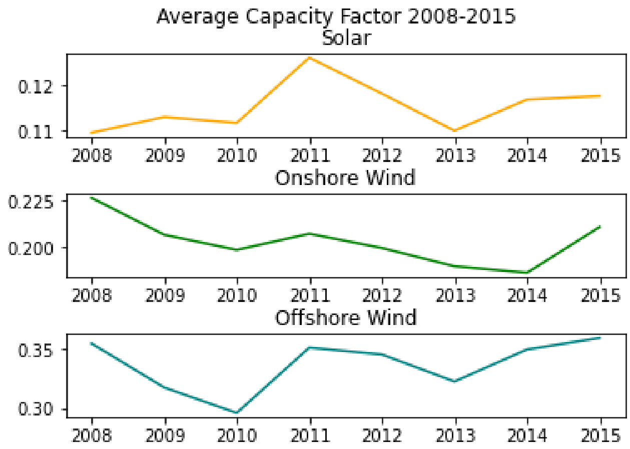
Figure 3: ***(a)*** *anticlockwise from onshore wind to hydro the energy from each source is [20.4% 20.0% 58.9% 0.7%]* ***(b)*** *anticlockwise from onshore wind to battery the energy from each source is [15.28% 34.43% 11.70% 19.72% 0.66% 8.66% 9.56%]*

	Install Capacity [GW]	Capacity factor [%]	Energy Dispatched [TWh]	Share of Total [%]
Onshore Wind	57,7	20.2	102.2	15.3
Solar	226.7	11.6	230.2	34.4
Gas	38.6	23.2	78.2	11.7
Offshore Wind	51.0	29.5	131.8	19.7
Hydro	11	4.6	4.4	0.7
H2	1525.7	0.9*	57.9	8.7
Batteries	148.8	9.8*	64.0	9.6

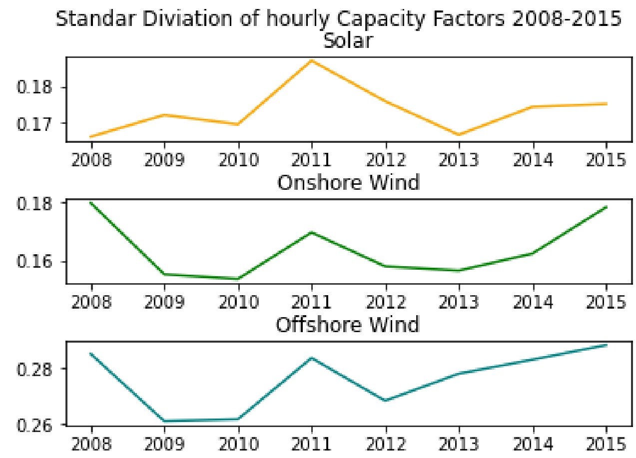
Table 3: *Optimal system with carbon cap at 90% reduction compared to 1990's levels.*
* *capacity factors included for storage technologies are a different measure than the capacity factors for generators and so should be directly compared. They are a measure of how often their total capacity is in use. The storage would be fully utilised and the factor would be equal to 1 if the storage was fully charged and discharge every 2 hours throughout the year.*

The change in electricity mix, (table 5a) as the emissions constraint changes from 60% to 100% reduction, shows a gradual increase in solar energy from 20% to 40% as the share of gas steadily decreases from 60% to 0%. Interestingly, we see a decrease in onshore wind, although this is replaced by a growing share of offshore wind which increase from 0% to about 20%, then decreases slightly as more storage is installed and then increases again as the carbon cap approaches 100%. It seems battery storage provides more electricity than hydrogen at emission reductions between 70% and 85% after which their share is more or less equal, rising to a maximum of 15% each at 100% reduction, the same level that onshore wind has decreased to. Curiously the graph shows a bump in the otherwise smooth curves in the carbon cap range of 95-100%. Solar energy and battery storage show a dip, while offshore wind and hydrogen see a bump. The effect is too large to be an error as the optimisation was run for every 1% change in carbon cap in this range, and the anomaly spreads over at least 3 percentage points.

Figure 6 shows the power dispatch during 3 days of winter and 3 days of early summer. The system can no longer use gas as a backup and so must use storage technologies. During the summer days plotted, there is more than enough solar power to meat the demand and so the storage technologies, hydrogen and batteries, can charge during this time. On the days of May 31st and June 2nd, the solar generation is large enough even to force the wind farms to curtail some of their power since the storage technologies are already charging at maximum



(a) *yearly capacity factors for renewables*



(b) *standard deviation of hourly capacity factors for renewables*

Figure 4: *Statistical properties of renewables due to inter-annual changes in weather in the period 2008-2015*

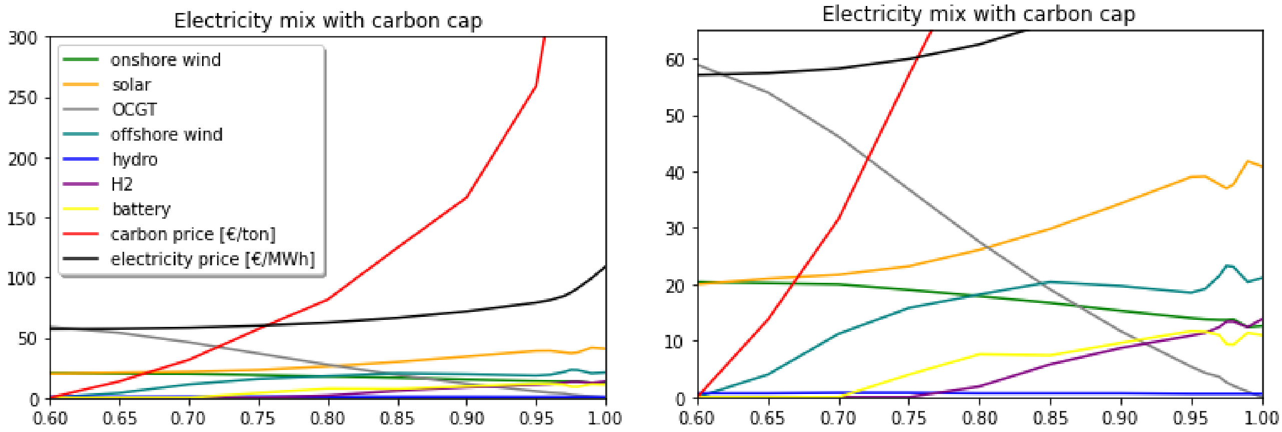
capacity and the system is isolated and so has no other countries to send it to. During the summer nights, it is sufficient for wind energy and the discharge of storage to meet the demand. Except for a brief period during the evening of June 1st, in which wind speeds have dropped and the hydrogen fuel cells combined with batteries are not enough to meet the demand, gas power is not used at all in the time plotted. During the 3 winter days plotted we see large amounts of wind energy being curtailed. The sharp changes in offshore wind power dispatch are not due to strange weather patterns but is a way for the system to balance out wanting to charge the storage technologies and cutting down on costs. The marginal costs for offshore wind farms has been set to 3€/MWh, twice that of onshore, and so the system is saving money by curtailing, since it cannot export the excess energy. This behaviour of switching on and off every hour might not necessarily reflect wind farm operations in the real world, however, during stormy days like the ones plotted here, it is not unlikely that wind speeds would reach cut-out (the point at which turbines must shut down to protect themselves from wind-speeds that are too high), leading a significant number of turbines to shut down across the country; so averaged out, it may be more realistic.

3.3 Connected System

So far the assumption has been that Germany's energy network exists in isolation, however this is far from true. Electricity can be exported to and imported from connected countries. It is beyond the scope of this paper to included every such possible connection in the synchronous grid of Continental Europe, however we will now see the effects of including just two neighbouring states, Denmark and France, modelled as separate nodes and connected to Germany via HVDC links.

Not all countries are created equal as regards natural resources, population size, or GDP. Denmark for example has no potential for traditional hydro electric power but does have some of the best wind resources in the world. What she lacks in land area and population size, she makes up for in capacity for offshore wind turbines and natural gas reserves. France, unlike both Germany and Denmark, has not opted to forgo nuclear power and as such still gets 80% of her electricity from fission.

However, the optimiser is not aware of these nuances unless limits are imposed that reflect these real world conditions. For example, if no constraints are imposed, the optimiser will place hundreds of gigawatts of onshore wind energy in Denmark, because the resources are good and the technology is relatively cheap. However, Denmark only has an average hourly demand of 3.7GWh so has no reason to install that much. Even if it wanted to export the huge surplus, it is limited in how much it can build by available land area and GDP. These last two limitations apply to all three countries and so a limit on the maximum install capacity was set to the average



(a) *carbon cap in range 60% to 100% reduction in emissions*

(b) *zoomed in version of* ***(a)***

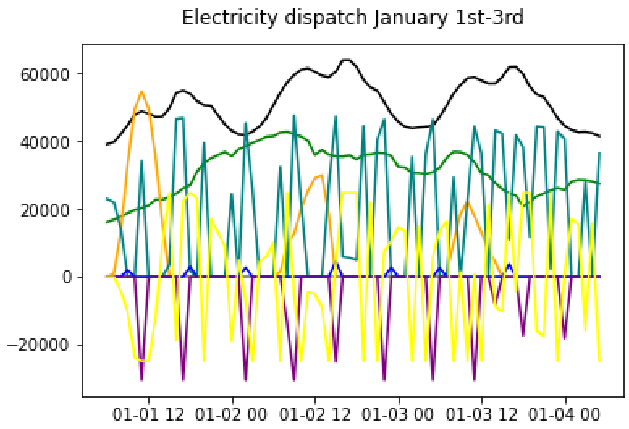
Figure 5: ***(a)*** *shows electricity mix as percentage of total, carbon price and electricity price with changing carbon cap from 60% to 100% reduction as compared to 1990 emissions level.* ***(b)*** *shows a zoomed in version in which the electricity mix is easier to make out.*

hourly demand in each country. This works out to be 3.7GW for Denmark, 57.7GW for Germany and 53.8GW for France. This was a simple way of limiting onshore wind at least somewhat fairly, such that the optimiser would not simply choose the country with best wind resources and place all windmills there. It would not be a realistic expectation that Denmark could afford to install windmills to supply a population 25 times that of its own. Denmark is already seeing most new wind farms being built offshore[**14**], so this limit is not unrealistic, however for Germany, who have as yet relatively little offshore wind, this limit is not high above the installation they currently have and so may be too harsh a constraint [**5**].

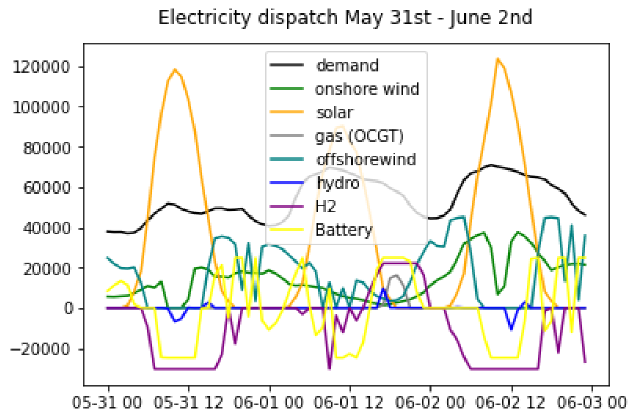
The same limit on land use is not valid for offshore, given that "sea area" is not used for other purposes like land might be used for agriculture and disturbance to local communities is diminished. However, Germany does not have a large coast (as compared relatively to Denmark and France) and costs will increase the further wind farms are built from the shore, and the GDP of a smaller country like Denmark should also limit how much they are able to build. The limits imposed for offshore were therefore 2 times the average hourly demand for Germany, and 10 times for Denmark and France. This leaves Germany with the ability to install 115.4GW of offshore wind, for comparison, the newly elected German government have proposed to install 70GW by 2045[**16**]. Solar power is also limited by population size (number of rooftops) and GDP. No limit was placed on Germany since they have been world leaders in solar energy and it seems likely that they will continue (the same proposal cited above foresees 200GW by 2030), however, a limit of 2 times average hourly demand was placed on both Denmark and France. Ideally the limits imposed would not be fixed but change over time, ie, the rate of installation would be fixed. In this way, a maximum per 10 years could be imposed based on current costs and GDP and then costs and limits could be updated on a 5 to 10 yeah basis, however this was not done here.

Similarly, the optimiser assumes unrealistically that energy trading is 100% efficient and cost free, which leads it to invest heavily in HVDC transmission lines. It is also unlikely that one nation would want to rely heavily on energy infrastructure in another country over which they have no control (part of the reason Germany is eager to install renewables is to become less dependent on Russian fossil fuels). For these reasons, I have limited link transmission capacities at one quarter of Germany's average hourly demand, which is about 14.4GW. For comparison, the world's largest transmission link, in China, has a capacity of 12GW[**15**]. Table 4a shows all constraints imposed for electricity demand only; in the following section, heating demand will be added, thus increasing average hourly demand, thereby increasing the constraints. These are given in table 4b. The nuclear energy capacity of France was initially limited to their current capacity of 60GW[**17**] but the constraint was not active and so was lifted when heating demand was added.

Germany will be connected to Denmark and to France, France and Denmark will not be connect, except through



(a) *dispatch in winter in MWh*



(b) *dispatch in summer in MWh*

Figure 6: *dispatch in Germany during 3 days in mid winter and early summer. Carbon cap is set to 90% reduction of 1990's levels. The system in isolated from other countries. The system can no longer use gas as a backup and so must use storage technologies.*

Germany. The limit of total carbon emissions of the system to 10% of Germany's 1990 emission levels remains in place, given that both Denmark and France have significantly lower emissions than Germany, this is not an impossible target for all 3 countries to achieve in the long run.

	DEU	DNK	FRA	active*
Onshore wind	57.7	3.7	53.8	All
Solar	-	7.5	107.6	None
Coal	0	-	-	None
Nuclear	0	0	60	DEU
Offshore wind	115.4	37.5	538	None
Hydro**	11	0	25	n/a
HVDC Link	14.4	14.4	14.4	All

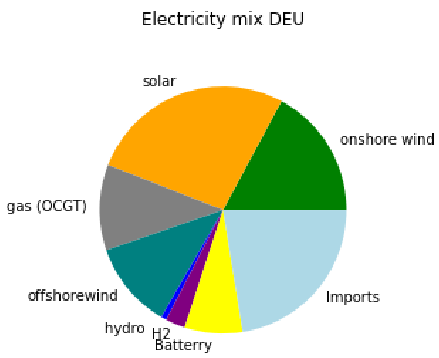
(a) *electricity demand only*

	DEU	DNK	FRA	active*
Onshore wind	151	9.9	109	All
Solar	-	19.8	218	None
Coal	0	-	-	None
Nuclear	0	0	-	DEU
Offshore wind	302	98.8	1089	None
Hydro**	11	0	25	n/a
HVDC Link	37.7	37.7	37.7	All

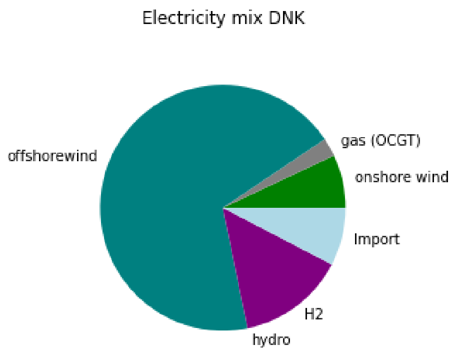
(b) *electricity and heating demand*

Table 4: *Maximum install capacities in GW acting as system constraints. *countries in which the constraint is active. **Hydro power is limited by current install capacity, assumed to be fully exploited.*

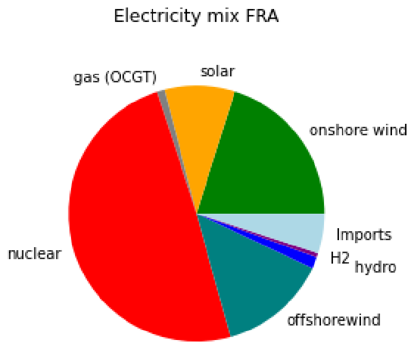
Figure 7 shows the electricity mix of each country. The primary changes for Germany's electricity mix are reductions in solar, offshore wind and hydrogen, these being replaced by imports. Germany's two neighbours invest heavily in one primary energy, for Denmark it is offshore wind and for France it is nuclear power, being 69% and 49% of their respective electricity mix. The magnitude is large enough that significant amounts of both are over produced and exported to Germany. For this reason, France needs almost no energy storage infrastructure as nuclear power serves as backup when renewables can't meet demand. Denmark, who's nuclear power is limited to zero (for sociopolitical reasons) must instead deploy hydrogen storage to balance when the wind drops, as well as imports from Germany along with a small percentage of gas power. Interestingly, no solar power is installed in Denmark, while this source remains as 27% of Germany's energy supply. Batteries are only found in Germany, likely to balance out solar. By connecting 3 countries that can trade energy across borders, the cost of electricity has fallen by 11% to 63.7€/MWh and the price of carbon needed to achieve 90% reduction in emissions (as relative to Germany 1990 levels only) had fallen by over 16% to 139.3€/ton despite the total demand being 200% of what it was before. The install capacities in Germany for every technology can be seen for the connected system in table 5.



(a) *17, 27, 11, 0, 0, 11, 0.7, 3, 8, 22*



(b) *7, 0, 2, 0, 0, 69, 0, 14, 0, 8*



(c) *20, 9, 1, 0, 49, 14, 1.5, 0.5, 0, 5*

Figure 7: *Electricity mix for each country in the co-optimised system. The numbers listed are % of total in the order: onshore wind, solar, gas, nuclear, offshore wind, hydro, H2, battery, imports*

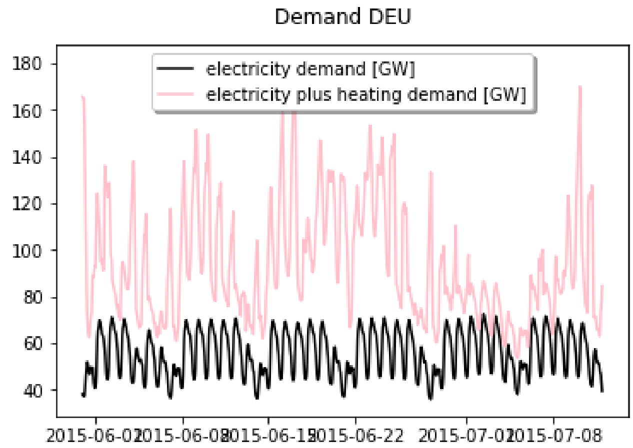
3.4 Sector Coupling

To achieve overall emission reduction targets it will be necessary in future to electrify different sectors of society. The transportation sector, for instance, is already undergoing a shift to electric motors in cars and city busses. Longer distance vehicles such as airplanes and ships will likely need to find alternative fuels, however it is probable that these fuels will be synthesised using electricity. Demand for heating will also need to be coupled to the electricity sector through the use of heat pumps. States like France who retain a large portion of traditional power plants (nuclear) could distribute waste heat in district heating networks, but others like Denmark who will see a larger penetration of renewables like solar and wind might not have any waste heat to use. Adding these sectors will result in a significant increase in the total electricity production and change the times at which electricity is in demand.

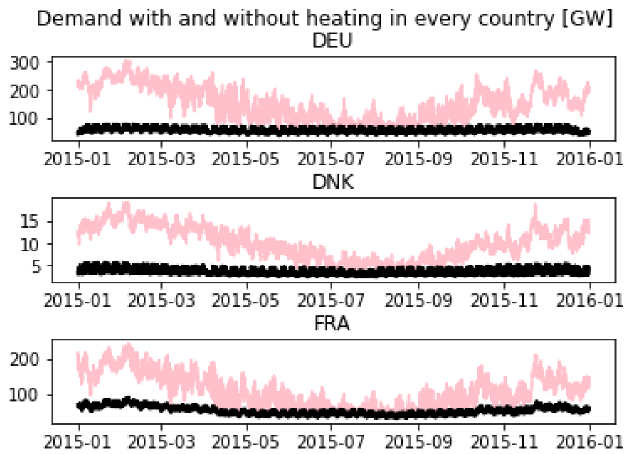
We will investigate the impact of adding 100% of heating demand to the electricity sector. To visualise the change in demand, figure 8a shows the electricity demand in Germany during 6 weeks of summer as well as the total demand, now including heating. It is clear that the regular weekly pattern of electricity demand alone is erased when heating is added, and although some daily regularity is maintained it is not as clearly defined. Figure 8b shows the change in demand when heating is added for each country on an annual scale. The total demand has increased by 2.6 times for Germany and Denmark while just 2.0 for France which has less heating demand due to its milder climate. While electricity demand was relatively stable throughout the year, adding heating leads to much higher demands during the winter as compared to summer. Ideally the magnitude of heating demand included here is an overestimate, not one hundred percent of today's heating demand will need to be electrified in future. By building newer, better insulated housing and retrofitting older homes to reduce heat loss, is is possible to significantly reduce energy requirements.

Figure 9 shows the electricity mix of the three countries when heating demand is included in each node. Possibly due to changes in demand variability just discussed, the results show a marked reduction in solar energy in Germany and France accompanied by a significant increase in offshore wind energy in Germany and increased imports by France. The new demand pattern is much better suited to wind energy as demand is high in winter and low in summer, much like wind speeds, and unlike solar energy which produced much more in summer compared to the winter months.

Gas power plants are also heavily reduced as a result of total demand increasing by 234% without lifting the carbon emissions constraint. Hydrogen storage is instead favoured in all three nodes the largest increases being in Germany and Denmark. The latter sees no significant changes other than slight reductions in wind energy and increased H2 storage and imports, possibly a result of Germany's large increase in offshore wind. The changes seen in Germany's production lead to changes in its storage, which now mostly uses hydrogen as opposed to batteries. This also leads to less reliance on imports. France retains 49% nuclear power and loses all of its solar power,



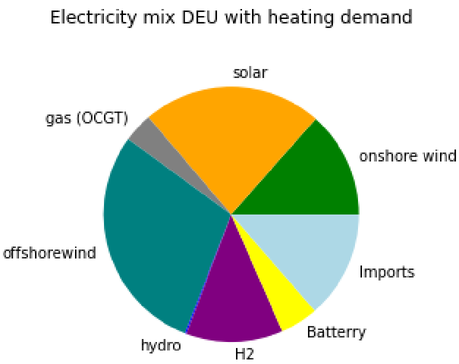
(a) *Demand of Germany during 6 weeks of summer*



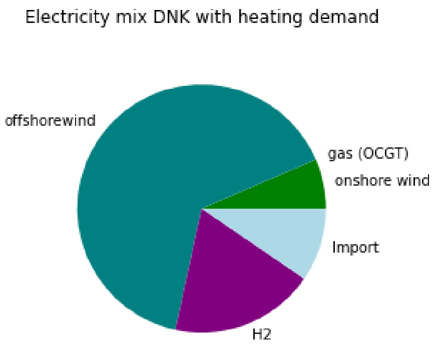
(b) *Demand for all countries throughout the whole year*

Figure 8: *When heating demand is added total demand increases 234%, for individual countries the values are 262% for Germany, 264% Denmark and 202% for France*

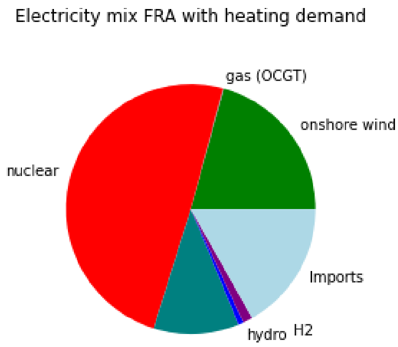
opting for imported electricity from Germany instead. The cost of electricity is now 90.3€/MWh, an increase of 42%, while the price of carbon is up 406% to 705.2€/ton. Germany's install capacities for every technology can be seen in table 5.



(a) *13(-4), 23(-4), 4(-7), 0(-), 0(-), 29(+18), 0.2(-0.5), 12(+9), 5(-3), 14(-8)*



(b) *6(-1), 0(-), 0(-2), 0(-), 0(-), 65(-4), 0(-), 18(+4), 0(-), 10(+2)*



(c) *21(+1), 0(-9), 0.1(-1), 0(-), 49(-), 11(-3), 0.7(-0.8), 1.3(+0.8), 0(-), 17(+12)*

Figure 9: *Electricity mix for each country in the co-optimised system with heating demand included. system carbon cap is set to 90% reduction compared to Germany's 1990's levels. The numbers listed are % of total for that country as well as the changes incurred by including heat demand in the order: onshore wind, solar, gas, nuclear, offshore wind, hydro, H2, battery, imports*

3.5 Speculation Time!!

In this last section we will speculate on some hypothetical change to the system. I thought it would be interesting to see how the connected system would react if France decided to follow Germany and phase out nuclear power. Not only would France need to replace 49% of its electricity mix, but Germany might not be able to rely as heavily on imports from that country and would likely need more storage capacity.

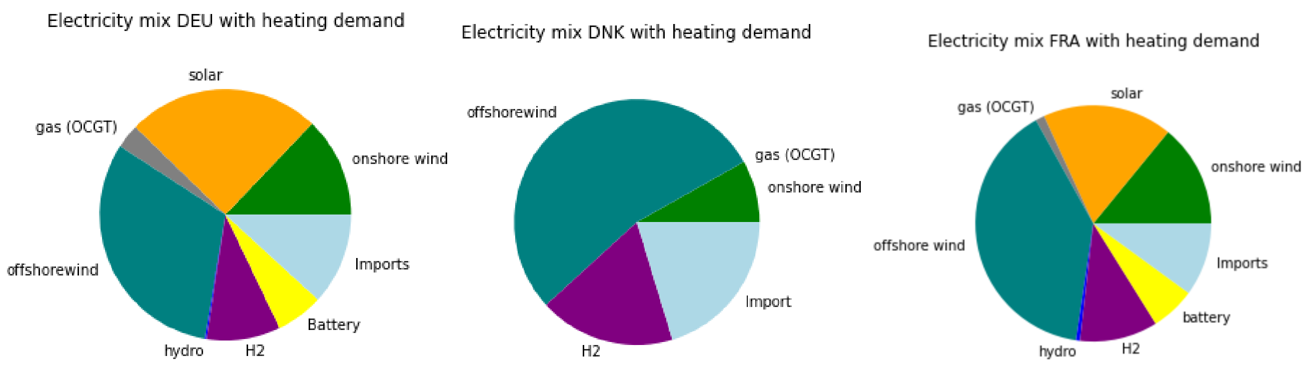
Th electricity mix under these conditions is seen in figure 10 and the changes in Germany's energy install capacities are given in table 5. The primary changes seen in Denmark are a substituting of some offshore wind energy for imported energy from Germany (Denmark is not directly connected to France). As Germany has only increase its share of offshore wind energy by 3 percentage points, this energy is likely coming from France which now has 40% of its total from this technology, up from just 11%. Surprisingly, Germany does not see any large changes in its electricity mix. Almost every technology, however, needs to be installed in larger capacities in Germany to balance out the loss of nuclear energy in France as well as the slight decrease in gas which gets placed in France instead og Germany. 18% of french electricity now comes from solar, up from 0%. Accompanying the large increases in renewables is storage infrastructure, which combine provides 17% electricity.

By adding this constraint, the resulting change in electricity cost is an increase of 10.3€/MWh to a total of 100.6€/MWh, while the price of carbon would increase by 90.6€/ton to a total of 795.8€/ton.

	install capacity[GW]	+ heat demand[GW]	no FRA Nuclear[GW]	capacity$_{max}$ [demand]**
Onshore wind	58*	151*	151*	1
Solar	162	456	470	-
Gas (OCGT)	43	142	119	-***
Coal	0	0	0	0
nuclear	0*	0*	0*	0
Offshore wind	23	216	288	2
Hydro	11*	11*	11*	11GW
H2 tank	276	9998	10921	-
H2 electrolysis	10	128	140	-
H2 fuel cell	6	144	167	-
Batteries	98	197	249	-
Battery inverter	17	33	39	-
Link DEU-DNK	14*	37.7*	37.7*	1/4
Link DEU-FRA	14*	37.7*	37.7*	1/4

Table 5: *Install capacities in Germany in 3 different scenarios: in the first column only electricity demand is included, in the second, heating demand is added, in the third we assume that France shuts down its nuclear power plants. In all scenarios, Germany is connect to both neighbours and the total system is subject to a carbon cap of 90% emissions reduction compared to Germany's 1990 levels.*

**Maximum install constraint is active.* ***Some technologies are limited with a max install capacity proportional to the average hourly demand. Hydro is limited to 11GW total and does not scale with demand.* ****Gas power is limited by emissions cap of 90% reduction*



(a) *13(-), 25(+2), 3(-1), 0(-), 0(-), 32(+3), 0.2(-), 9(-3), 6(+1), 12(-2)*

(b) *8(+2), 0(-), 0(-), 0(-), 0(-), 54(-11), 0(-), 18(-), 0(-), 20(+10)*

(c) *14(-7), 18(+18), 1(+1), 0(-), 0(-49), 40(+29), 0.6(-0.1), 11(+10), 6(+6), 10(-7)*

Figure 10: *Electricity mix for each country in the co-optimised system with heating demand included under the condition that France opts out of nuclear energy like both of the other countries. System carbon cap is set to 90% reduction compared to Germany's 1990's levels. The numbers listed are % of total for that country as well as the changes incurred by including the no nuclear constraint in the order: onshore wind, solar, gas, nuclear, offshore wind, hydro, H2, battery, imports*

My PyPSA code used in this project can be found at:
https://github.com/bdbsimonsen/RES_Project_2022/blob/main/RES_Project.py

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