Predictive Scenario Modeling of Germany's Electricity Mix

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Abstract

This project's goal is to make a model using the GAMS modeling system to predict investments in new installed capacity in Germany, by considering current costs and predictions of cost developments for different energy generation and storage technologies. Carbon capture and storage is extra emphasized as a new technology into the model, with the intention of finding out if there is a path for this controversial technology in Germany. The results show a suspected trend of more renewables penetrating the system and an increase in CCS in place of regular gas power. It also predicts a big increase in battery storage capacity. While some of the assumptions in the model makes it little useful for practical purposes, it highlights some possible trends for the German electricity system.

Contents

1 Introduction

In order to reach the ambitious climate targets set by the Paris Agreement, it is not only necessary to cut emissions with low or zero emission technologies, but also to develop and implement negative emission technologies to abate for the hard-to-decarbonise sectors. The IPCC and IEA stresses that large scale implementation of CCS technologies is a necessity in order to reach the climate targets[3].

In Europe's energy system, one of the most in important Countries in the ongoing energy transition is Germany. They are world leading in the deployment of solar and wind power, ranking 4th and 3rd respectively [10] [13]. They have also managed to reduce their emissions by over 30 percent compared to 1990 levels[7], really stepping forward as a leader in the green shift in Europe. Despite this, Germany is still by far the largest emitter in Europe, releasing 810 million tonnes of CO2 equivalents in 2019[12].

1.1 Literature review

While putting an enormous effort into deploying low and zero emission technologies, carbon capture and storage has not been welcomed in the same manner in the public and among politicians. A study by Carbon Limits AS and THEMA Consulting Group in 2020[6] found that Germany has 183 large facilities where CCS could be implemented in the industry and energy sector. The calculated capturable quantity ranges from 37-89 MtCO2/y. The high potential represents 11 percent of total German GHG emissions, based on 2017 values. In the report, it is also referred to the Federal Institute for Geosciences and Natural Resources (BGR), who states that Germany has a carbon storage potential of 9.1 Gt onshore and 2.9 Gt located offshore in the North Sea. Despite the seemingly good potential for CCS in Germany, there has been a lot of opposition from the public, much because of the controversy of onshore storage. The German CCS act, introduced in 2012, halted all CCS projects except for testing and demonstration pilots. Under the current legal framework, it is thus not possible to start a CCS project in Germany. Another study by Tor Håkon Inderberg and Jørgen Wettestad[8] explored the different policy outcomes of CCS for Germany and the UK, where the UK has already contracted two specific CCS projects, with explicit timelines for realisation. The study found two main reasons for UK's favourable policies compared to Germany. The first one is their much larger offshore storage capacity, which evokes less conflict among the public. The second one is their (and Germany's lack of) oil-industry expertise, which makes their task easier. Because of the fact that Germany to date does not have any plans for CCS projects, the papers found in this literature review were mostly focused on policies and policy changes and not on the techno-economic perspective.

1.2 Research question

Despite the lack of initiative for CCS in Germany up until now, Chancellor Angela Merkel gained a few headlines when she stated in 2019 that CCS would be necessary to achieve the climate targets. Assuming that the current policies will change and set the stage for rapid development of CCS, this paper will explore its potential through predictive scenarios of declining costs for various technologies, including CCS. Germany has decided to reach net zero emissions by 2050, which will require phasing out the fossil fuels in their electricity generation mix. The demand will then have to be covered by new technologies such as solar PV, onshore and offshore wind. Due to the intermittency of VRE technologies, generation from gas will also still be required for flexibility in the system, and that is where the carbon capture enters the picture, since these plants can be fitted with CCS. There is a lot of literature on technology learning and predictions of technology costs towards 2050. Using this information, and in addition forecasts of the ETS carbon tax, this paper asks:

How will changes in technology costs and carbon tax affect Germany's electricity mix? Will CCS become a viable option?

To answer this, an optimisation model will be made using GAMS to predict investments in new generation technologies and storage. The model will include seven scenarios, one for every five years from 2020 until 2050. The scenarios will differ in terms of technology costs and the ETS carbon tax. Technology costs and predictions of their development, demand for new capacity, and forecasts of the carbon tax will be the inputs for the model in each scenario. The resulting outputs will be the installed capacity of different technologies, their generation and total system cost. In the next section, the model will be further explained.

2 Methodology

In this section, the model development will be explained in detail. First the data will be presented, then the model will be described. The technologies considered in the model will be solar PV, onshore wind power, CCGT (gas) and CCGT with CCS.

2.1 Data

For the predictions of technology costs, the resolution varied by source. Some sources had a prediction every year until 2050, while others had only one for 2020 and one for 2050. In order to create a model for every five years, it is therefore assumed a linear relationship between costs where the source does not provide sufficiently high resolution.

Technology costs

Investment costs for PV and wind are obtained from the international energy agency[11]. For CCGT and CCGT + CCS, the global CCS institute[2] and Budinis et al[1] provided good sources for current costs and forecasts to 2050, respectively.

In figure 1-5, the cost forecasts for the different technologies every five years is shown.

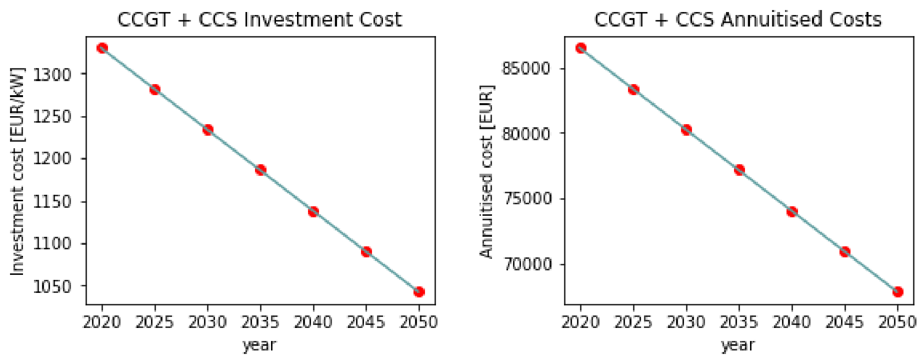

Figure 1: Forecast of CCGT + CCS costs

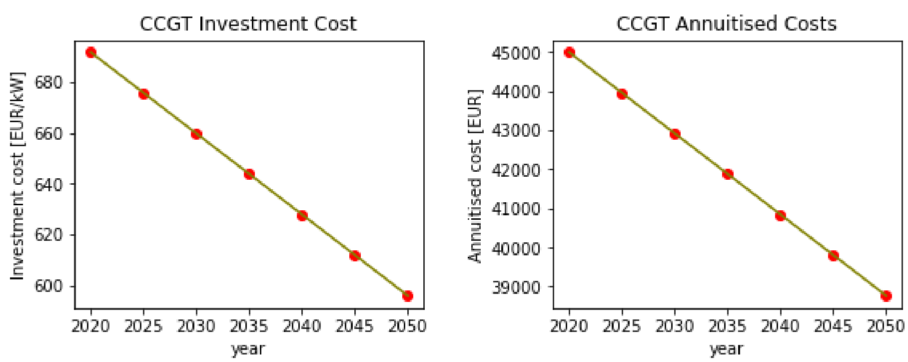

Figure 2: Forecast of CCGT costs

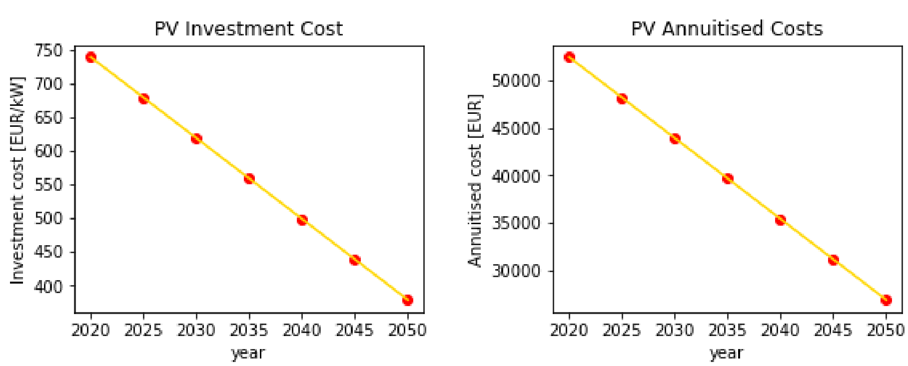

Figure 3: Forecast of PV costs

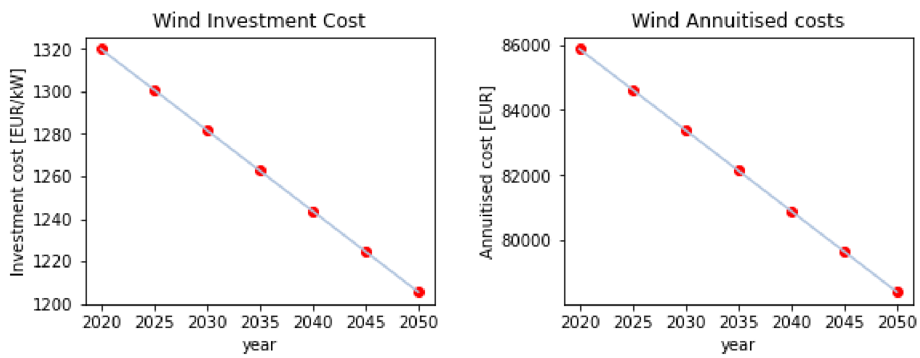

Figure 4: Forecast of wind power costs

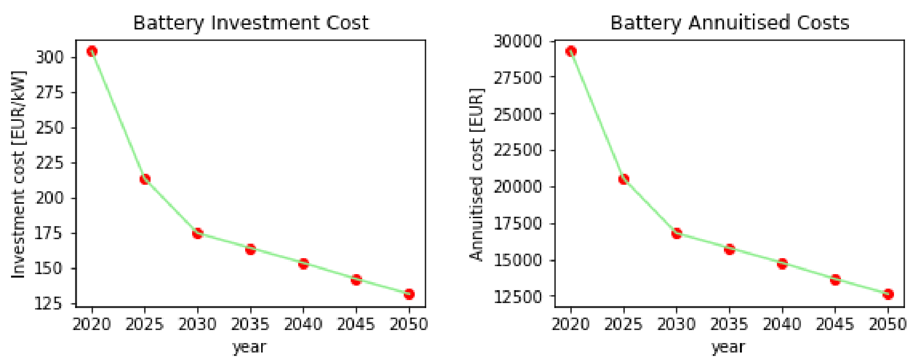

Figure 5: Forecast of battery storage costs

Demand

This model will only predict new installed capacity, not taking the current electricity mix into consideration. The demand for new capacity will then be the portion of the demand which is today covered by technologies that needs to be phased out, plus the eventual increase in demand towards 2050. It is predicted by the German Environment Agency that the demand in 2050 will be 506 TWh[4], compared to 495 TWh in 2019[5], in other words only a 2% increase. The reason for this is that increased demand from electrification is cancelled out by more efficient technologies, demand side response and other efficiency measures in the system. In the model, the demand is therefore assumed to only be the portion of today's demand that is going to be replaced by new generation technologies. In Germany, this is mainly coal and nuclear, which is assumed in the model to be the only ones phased out. Combined, they make up 36.5% of the electricity mix, so the 2019 demand is scaled by a factor of 0.365 in order to get the demand for new capacity. This formulation does not consider import and export of electricity and it also assumes an instantaneous phase-out of coal and nuclear in each of the scenarios.

The scaled demand is shown in figure 6.

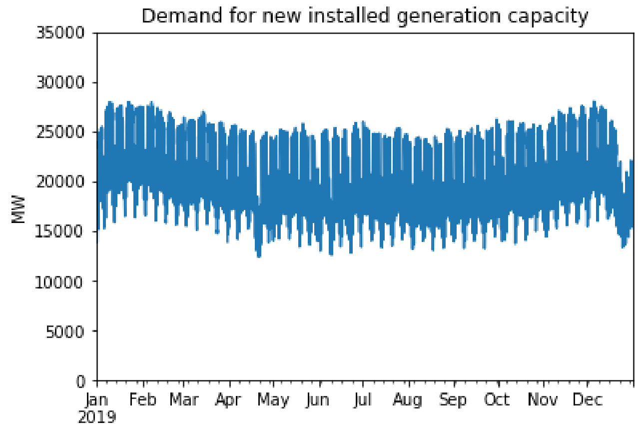

Figure 6: Demand in Germany, scaled by requirement for new generation capacity

Carbon tax

CO2 price predictions are obtained from the International Energy Agency[9]. Prices following a trend of stated policies are included as well as prices based on the net-zero 2050 scenario. This model will use the stated policy based prices.

The forecast of the carbon tax in both scenarios are shown in figure 7.

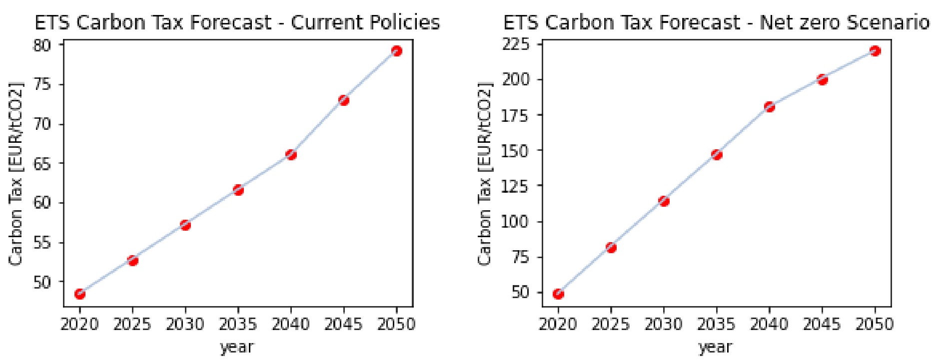

Figure 7: Forecast of carbon tax

2.2 The model

As mentioned in the introduction, the model will be used to create seven independent scenarios, one every five years from 2020 to 2050. The result for each scenario will then be the new capacity that would be invested in, in that particular year, with the forecasted costs and carbon taxes as input.

The model's objective function is to minimise the total system costs. The total system cost is formulated as follows.

$$Z = min\left[\sum_{t} C_{tec,t} + \sum_{t}\sum_{h} C^{h}_{var,t} + \sum_{t}\sum_{h} C^{h}_{emi,t}\right] \tag{1}$$

Where $C_{tec,t}$ is the annuitised costs for each technology including battery storage, $C^{h}_{var,t}$ is the variable costs for each technology each hour and $C^h_{emi,t}$ is the cost of emissions for each technology each hour.

The annuitised costs, variable costs and emission costs are calculated, respectively, by the following formulas

$$C_{tec,t} = \frac{I_0}{\sum_t \frac{1}{(1+r)^t}} \tag{2}$$

Where r is the discount rate. 5% is used for all technologies in this model.

$$C^h_{var,t} = \frac{f}{\eta} + vom \tag{3}$$

Where f is fuel cost, η is the fuel efficiency and vom are the variable operation & maintenance costs.

$$C^h_{emi,t} = E_f \times C_{tax} \tag{4}$$

Where E_f is the CO2 emission factor for each technology and C_{tax} is the carbon tax.

3 Results

In this section, the resulting installed generation and storage capacities, as well as system costs will be presented. The output of the GAMS model was exported as a database file and accessed in Python, where the figures were created.

3.1 Installed generation capacity

Figure 8 shows the installed capacities of the different generation technologies. The first noticeable thing is the increase in total capacity for each scenario, which comes mainly from the doubling of PV, from 29380 MW in the 2020 scenario to 59415 MW in 2050. The share of gas with CCS also increases a good portion, from 13264 MW to 15803 MW installed. Gas without CCS is reduced from 16002 MW to only 7857 MW, while wind power is fairly stable throughout the scenarios, but has a slight decrease from 27806 MW in 2020 to 25550 MW in 2050.

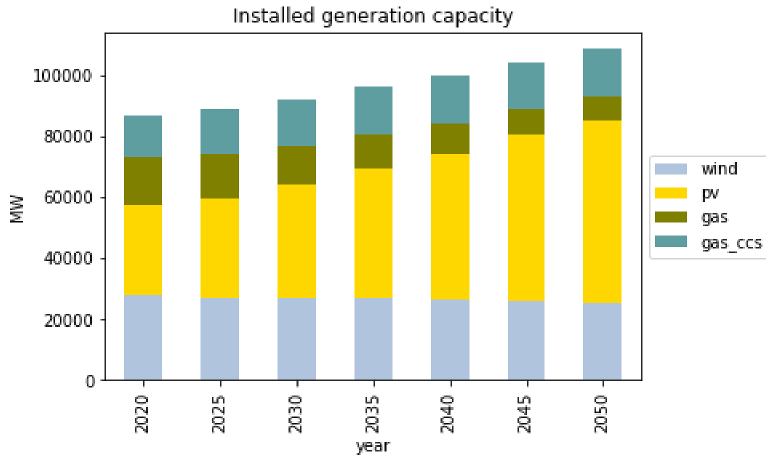

Figure 8: Bar plot of new generation capacity in each scenario, showing a high increase in PV installation, decreasing gas installations and a moderate increase in gas with CCS.

3.2 Installed storage capacity

Moving on to energy storage, figure 9 shows a huge increase in installed battery storage over the scenarios, from 1279 MWh installed in the 2020 scenario to 36269 MWh installed capacity in 2050.

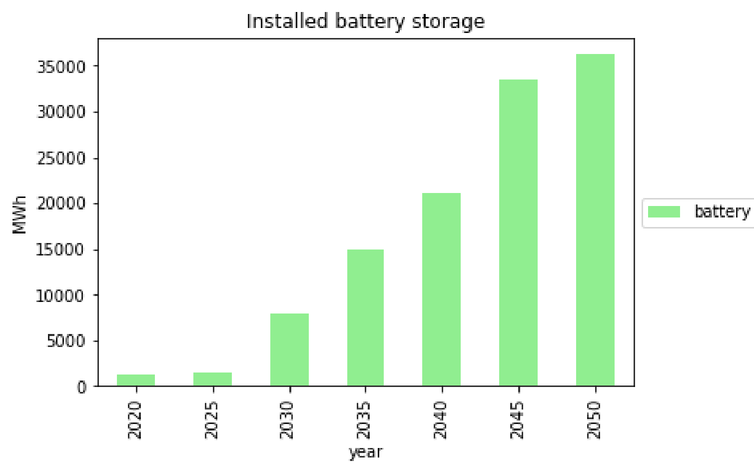

Figure 9: Bar plot showing a major increase in battery storage in the seven scenarios

3.3 Total system cost

Finally, figure 10 shows the total system cost for all of the scenarios. The cost goes from 11,55 billion Euros in 2020 to 9.97 billion in 2050, a decrease of 14 %.

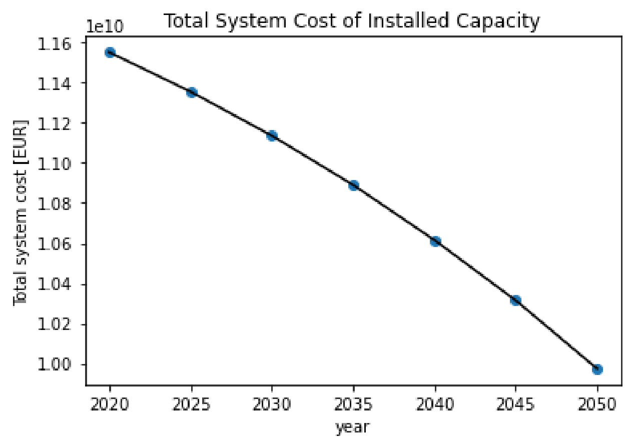

Figure 10: Total system costs of new installed capacity

4 Discussion

When evaluating the results from a model, it is important to be aware of the assumptions that has been made and not to draw conclusions without critically assessing these. In this particular model, due to limited time and little experience with GAMS, there are a couple of major assumptions which will be pointed out before the results are discussed.

- *Storage ramp speed*

  The battery storage capacity in this model have no limit of ramp-speed, meaning that in can in theory release its whole capacity in one hour and fully charge back up in the next.

- *import/export*

  Germany does not operate in island mode, being relies heavily on electricity trading with other EU countries. More so than many other countries because of their increasing share of VRE's.

- *Additional CCS costs*

  In the model, only the capturing of the CO2 is included in the costs and not transport and storage. The reason for this is that the latter varies greatly by transporting distance and storage location. It was therefore decided to simplify the model by only considering capture costs.

With the main assumptions in mind, the results can now be analysed.

1. Installed capacity and electricity mix

The demand was kept the same throughout all of the scenarios, so a natural question to ask is why the total installed capacity is increasing for each scenario. The answer is most likely rooted in the intermittency of

VREs. With an increasing share of solar power in each scenario, the installed capacity would have to be larger in order to meet the demand, not taking storage into consideration. In the first scenarios, where the cost of gas is competitive and the carbon tax is sufficiently low, a relatively low amount of gas power (and gas + CCS) takes care of the flexibility. When the carbon tax increases and cost of solar rapidly decreases, it becomes economically favourable to install a larger capacity of PV than a small, flexible amount of gas.

Isolating the gas power and gas with CCS reveals another promising development, seen from a climate perspective. Regular gas power has a slight majority of the share in the first scenarios, but gradually they switch roles and CCS becomes dominant. When figure 1 and 2 from the methodology section is compared, it can be seen that the CCS costs drops way more than for regular gas. This, combined with the carbon tax, results in investments being more favourable for gas with CCS.

Finally, we have wind power which does not change much through the scenarios. From the cost predictions in figure 4 we see that the costs do not decrease significantly towards 2050. This can be justified with onshore wind now being a very mature technology and a lot of research is now going into making offshore wind cheaper. There is still a lot of potential for onshore wind, but less investments in new capacity in favour of other technologies might be a realistic scenario.

2. Installed storage capacity

The huge increase in battery storage comes as a result of both rapidly decreasing costs, from an annuitised cost of 29250 EUR in 2020 down to only 12632 EUR in 2050, and the increasing need for flexibility in an increasingly solar dominated electricity system. Even though the actual numbers might not be accurate, an enormous increase in utility scale storage capacity is predicted to be required in the next decades, supporting the validity of the results of the model.

3. Total system costs

Decreasing system costs is logical in this model, with a constant demand and technologies with decreasing prices required to meet it. We all know that the green transition will not be free, but looking exclusively at new installed capacity, this will become cheaper as technology matures.

5 Conclusion and further work

In this project, I have attempted to create a model for the German electricity system. The model was used to develop seven scenarios where changes in technology costs and carbon taxes decided investments in different technologies each five-year period from 2020 to 2050. Some major assumptions prevent the model from being realistic enough for practical uses, but it shows a trend of development which is likely to be somewhat correct.

The research question asked how changes in costs and carbon tax would affect Germany's electricity mix, and if CCS would become a viable option.

For the first part of the research question, the model clearly shows a trend of more renewable energy as the costs are predicted to decrease at a rapid pace, mainly for solar power. Battery storage will also become an important part of the electricity system, providing much needed flexibility in the place of fossil fuel based flexible power plants today.

The second part of the research question regarding CCS is more difficult to draw conclusions about. The prospects are good according to the model, where gas with CCS gradually becomes more dominant than regular gas power plants as costs decrease and carbon tax increases. However, there are many variables not taken into account in the model. One of them is already mentioned, regarding the cost of transportation and storage. Another major part is the political feasibility. As discussed in the introduction, there is little political will and even less public will to implement large scale CCS in Germany. It will be interesting to see the policy developments over the next years, but for now there will be no CCS in Germany.

As an ending remark, there are a few things that would be interesting to consider for further work. The first one is to include offshore wind as a technology, as Germany is putting a lot of effort and capital into it's development. It would then be interesting to compare with onshore wind in the model. In order to make a more confident conclusion regarding CCS, further work would be to make realistic cost estimates that include transportation and storage. The politics is unfortunately harder to incorporate into the model. It may be possible to include some kind of political/public opposition penalty cost in the model, but this will be for others to explore.

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