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Analysis of CO2-emissions and power market consequences from electrification of offshore petroleum installations

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Abstract

Electrification of Utsira is planned with a start-up in 2022 and will greatly increase the power demand in the southern part of Norway. By simulating the future Nordic power system, the aim of this thesis is to analyze the impact of an electrification on the power system. Areas of focus will be power production, emissions, power prices and power exchange.

The results show that the total emissions in the system in 2055 compared to 2019 is about one third. This is mostly due to a great increase in installed wind capacity. At the same time, thermal power production is reduced greatly. Electrification will lead to slightly higher emissions, but as the power system has an increasing share of renewable power production the net emissions change after electrification is still negative.

Sammendrag

Elektrifisering av Utsira er planlagt med en oppstart i 2022 og vil øke kraftbehovet i Sør-Norge betraktelig. Ved å simulere det fremtidige nordiske kraftsystemet er målet med denne oppgaven å analysere hvilken påvirkning en elektrifisering har på kraftsystemet. Fokusområder vil være kraftproduksjon, utslipp, kraftpriser og kraftoverføring.

Resultatene viser at utslippene i systemet i 2055 sammenlignet med 2019 er omtrent en tredjedel. Dette skyldes hovedsakelig en stor økning i installert vindkraft. Samtidig reduseres termisk kraftproduksjon betraktelig. Elektrifisering vil føre til litt høyere utslipp, men ettersom kraftsystemet får en høyere andel fornybar energiproduksjon vil netto utslippsendring etter elektrifisering fortsatt være negativ.

Preface

This thesis is a continuation of my project work during the 1^{st} semester of my last year on this study programme. The first part of the work focused mainly on emissions related to the electrification of Utsira, whereas this master thesis also includes study of the entire Nordic power system.

I would like to thank Magnus Korpås for guidance and good ideas, as well as for always having simple solutions to any problems I might have had.

I would also like to thank Hossein Farahmand for help with the GAMS model as well as for getting a better understanding for the model results.

Without Xiaomei Cheng's help with the GAMS model I would most likely still be trying to start the first simulation, so a great thanks to her aswell.

Haavard Haugse

Contents

1 Introduction

In the years to come, large scale wind and solar power projects will rise to life. Investing in renewable energy is in the wind, at the expense of other non-renewable ways of producing power. Electricity demand is rising as a result of electrification of industry and transportation, which is turn requires heavy investments in infrastructure for transmitting and producing power.

New cross border transmission cables are planned and being built to link markets together as well as increasing the security of supply. In Norway, electrification of offshore petroleum installations is a hot topic. Utsira is one of the areas where an electrification is planned, with a start-up in the early 2020s. The power demand following this electrification will be significant compared to the normal demand in the afflicted area, presumably impacting both power prices and security of supply. The driving force behind supplying offshore petroleum installations with PFS is to reduce overall CO_2 emissions.

The aim of this master thesis will be to analyze the power market consequences of an electrification of Utsira by simulating the future Nordic power system. Areas of interest in this analysis will be power prices, changes in power production, cross-border power exchange and general changes to the power system. Eventually, and maybe most importantly, a quantification of CO_2 emissions related to electrification will be done. A big part of the work will also include getting familiar with the power system model and develop it further to build a more complex model base.

2 Theory

2.1 Electrification of Norwegian offshore petroleum installations

In 2014, decisions were made to supply Utsirahøyden with power from shore [18], with a start-up in 2022. The ultimate goal of electrifying any offshore petroleum installation is to reduce the emissions and thus limiting the impact of such industry on the climate. The oil and gas industry in Norway is responsible for about one fourth of the total emissions in the country [16], making it a natural place to reduce emissions.

An argument against electrification is that the gas saved by avoiding the use of offshore gas turbines will still be used elsewhere, leaving the total global emissions unchanged. As long as all the gas is transported to shore and used for heating or other power intensive industry this will be true. However, there are slight savings in emissions due to the fact that offshore gas turbines often have a lower efficiency.

When global power industry reaches a point where renewable energy production devalues petroleum industry in such a way that it is no longer economically feasible to produce oil and gas at maximum capacity; that is when the global emissions will see the biggest impact of electrification. In other words; electrification has a bigger impact when it leads to a reduction in gas production (primarily the gas that earlier was used to supply the platforms with power and heat).

2.2 The Nordic power system

The Norwegian power system is continuously being developed as new challenges and projects are brought to life. Since the first electrical installations were built in the late 19th century, the power system has seen immense improvements and is now covering most of the country. See figure (2) for some important dates in Norwegian power history.

From being a system where many installations were supplied by dedicated sources [3], to a country-wide grid which can transfer power over long distances, Norway has certainly secured a robust and well working power system.

Hydro power is one of the reasons why the power system in the western part of Norway is so extensive. In a normal year about 130 TWh of hydro power is produced, making it the single most important way of producing power. NVE has calculated the total economically feasible hydro power resources to be 214 TWh, where 130 of these are already installed [6]. As we can see

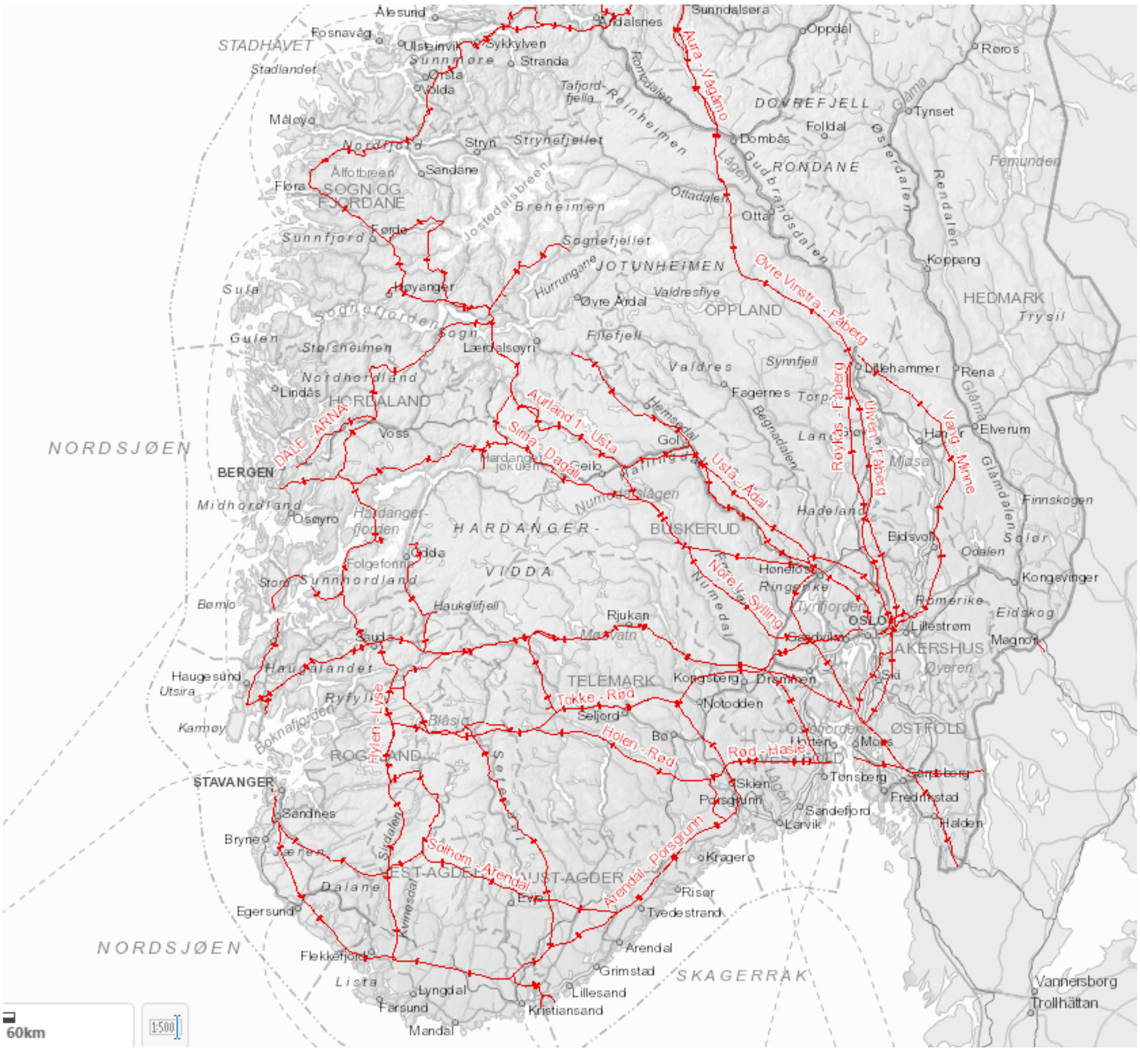


Figure 1: Central grid in Southern Norway. Map provided by NVE Atlas[5].

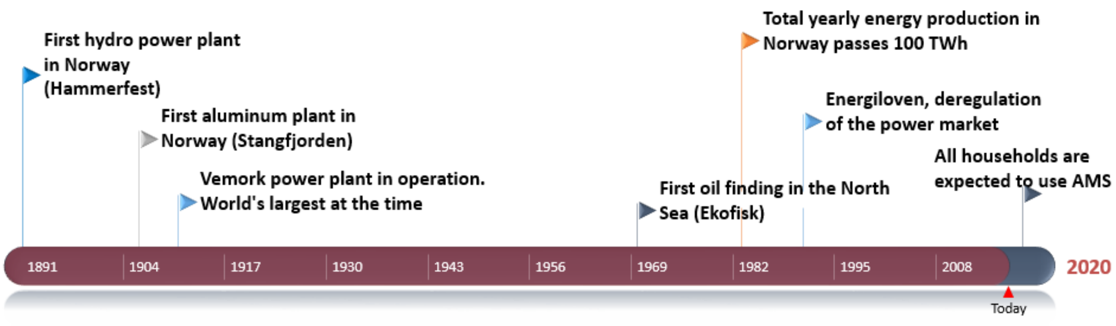


Figure 2: Important dates in Norwegian power history.

in Figure (1) there are 420 and 300 kV lines in towards all the major hydro power areas (E.g. Tonstad, Kvilldal, Aurland, Sima).

Along with the biggest hydro power plants we find aluminum plants. As examples, Sunndalsøra and Øvre Årdal both have aluminum plants located close to large hydro power plants. Production of aluminum is a very energy intensive industry and it is therefore necessary to build these plants close to power plants that can deliver the required power to avoid high transmission losses. The aluminum plant in Sunndalsøra requires more than 5 TWh of energy each year, while the total power production in Sunndal is about 2.7 TWh [7].

Electrification of the transportation sector also displays challenges to the power system in Norway. Infrastructure for electrical vehicles, ferries (figure (3)), even for aquaculture industry, is expected to become a big challenge in the coming years [17].

Figure 3: The electrically powered ferry between Oppedal and Lavik, *Ampere*.

With the already developed hydro power and power intensive industry in the western part of Norway, the power system has a good foundation for supporting electrification of offshore petroleum installations. In addition to the current state of the power system, with an electrification there has to be many new installations and changes, e.g. transformers and increasing transmission capacity if necessary.

2.3 GAMS

A model for the future Nordic power system has been made in the program GAMS. This is a program used to solve complex mathematical optimization problems, using linear, non linear and MIP optimization solvers.

Credits to Xiaomei Cheng and Hossein Farahmand for developing the GAMS model that will be used for this thesis.

Figure 4: GAMS logo.

2.4 Connecting the Nordic countries

The first sea cables from Norway to any other country were Skagerrak 1 & 2 in 1977. They both have a transmission capacity of 250 MW, and have been contributing to the security of supply since they were installed.

The driving force behind building sea cables and increased transmission capacity between the Nordic countries is the increased security of supply. Power cuts will be less frequent and customers will experience less extreme power prices. Some areas will experience changes in the power price as a direct result of the cables[1].

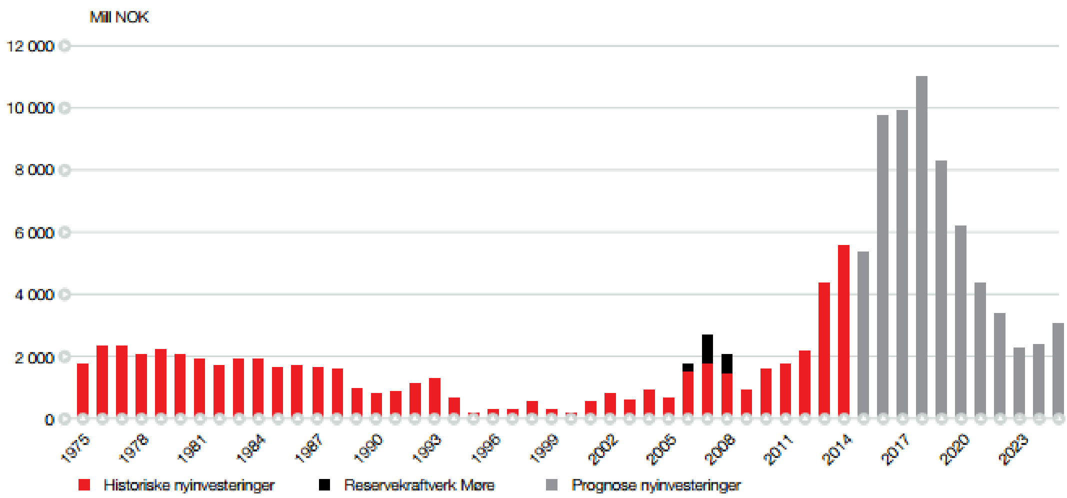


Figure 5: Statnett's yearly invesment amount. Historical values referred to 2015 values. Figure provided by Statnett[9].

Statnett is the TSO in Norway. In the *Grid development plan*[9] from 2015, Statnett plans to make investments in the grid equal to 50-70 mrd. NOK towards 2030. Statnett's overall goal is to build "the next generation's central grid", meaning a grid that can handle future power system projects and maintain the security of supply. Figure (5) shows historical and planned investment amounts.

In 2020, a sea cable from Norway to Germany is expected to be finished (NordLink). This will be a 1400 MW transmission cable from Tonstad, Norway, to Wilster, Germany. The driving force behind this project is to increase the security of supply as well as prepare the power system for the growing renewable energy production in Germany. When Germany experiences surplus power from wind and solar production, this can be sold to Norway. This way the prices will even out in the connected areas, avoiding very low and very high power prices [10].

Below is a table showing finished and planned projects in the connection of the Nordic countries' power system.

Table 1: Some finished and planned cross-border transmission projects.

Project	**Year**	**Description**
NorNed	2008	700 MW subsea cable between Kvinesdal, Norway, and Eemshaven, Netherlands.
Skagerrak 4	2014	Adds 700 MW to the already 1000 MW installed transfer capacity between Norway and Denmark.
Cobra	2019	700 MW subsea cable between Eemshaven, Netherlands, and Esbjerg, Denmark.
NordLink	2020	1400 MW, 525kV subsea cable between Tonstad, Norway, and Wilster, Germany.
NSL	2021	1400 MW, 500 kV subsea cable between Kvilldal, Norway, and Blyth, UK.
VikingLink	2022	1400 MW subsea cable between Lincolnshire, UK, and Jutland, Denmark.
Hansa PowerBridge	2025/2026	700 MW subsea cable between Germany and Sweden.

2.5 Input parameters

2.5.1 Load data

The load data which is used in the GAMS code is given as a one year load with hourly power demands. This means that the load input to each iteration (year) in the code is the same, only changing with the electrification load in area a1 which is the southern part of Norway.

Electrification of the transport and heat sector will increase the power demand. In total, an increase of as much as 50 TWh in the Nordic countries is likely towards 2040, as indicated by Stanett[13]. It is therefore important to know that our model does not take into account this increase in power demand.

2.5.2 WEO 2016 - Scenarios for CO_2 and fuel prices

The CO_2 and fuel prices in the GAMS model is collected from World Energy Outlook 2016[14]. WEO 2016 operates with three different analysis scenarios; "New policies", "Current policies" and "450 scenario". From IAS' webpage[15], we find the description of each scenario.

New policies scenario

"New Policies Scenario of the World Energy Outlook broadly serves as the IEA baseline scenario. It takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse-gas emissions and plans to phase out fossil-energy subsidies, even if the measures to implement these commitments have yet to be identified or announced."

Current policies scenario

"Current Policies Scenario assumes no changes in policies from the mid-point of the year of publication (previously called the Reference Scenario)."

450 scenario

"450 Scenario sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2."

WEO 2016 gives a forecast for the CO_2 and fuel prices to 2058. For the first 2030 and 2060 simulations, the "current policies" scenario has been used. See figure (6) for the CO_2 prices.

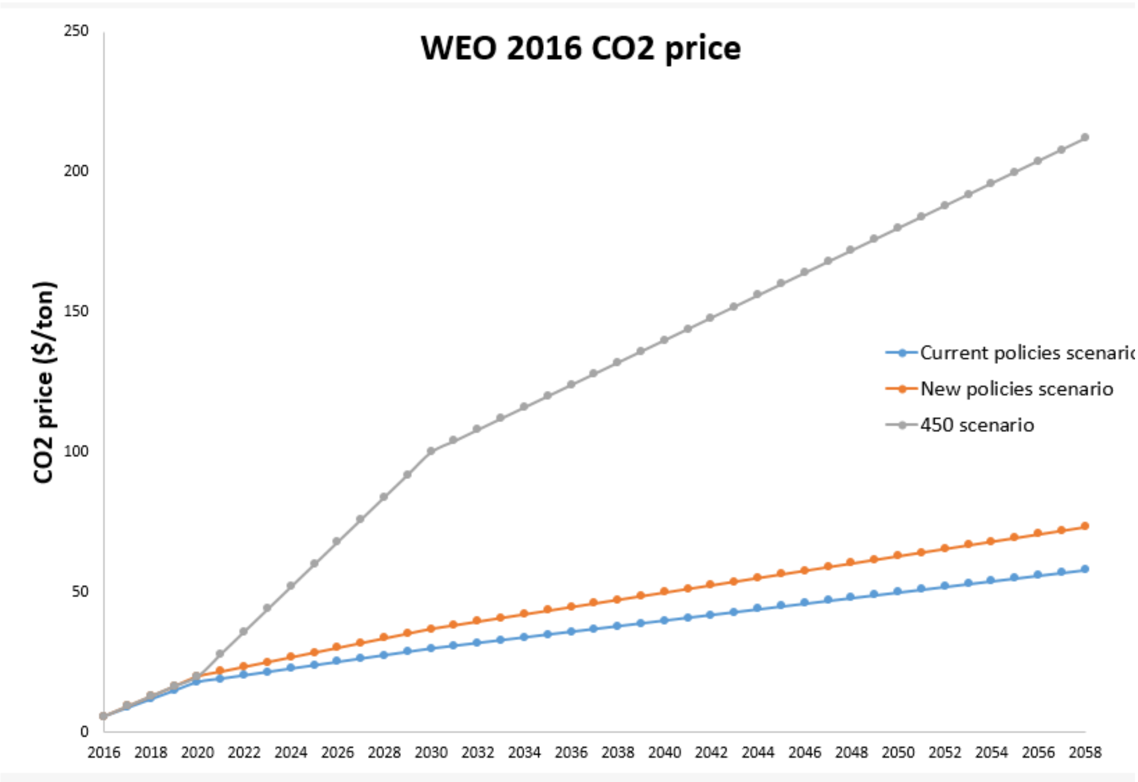


Figure 6: WEO 2016 CO2 price forecast for three different scenarios.

3 Historical model

The aim of analyzing the historical model is to get to know how it works and which results we can expect from this model. With the results from the historical model we can know better how to put results from the 2030 and 2060 model into context, i.e. learn how the results should be scaled or looked at compared to historical data.

To test the model, we first do a simulation for the year 2010. As explained further on in this section, two different models has been used to simulate year 2010. Both models aim to get results that are comparable with historical ENTSO-E data[11].

3.1 Year 2010 in energy

A normal hydro power year in Norway is normally characterized by more export than import. Since year 2000 the average yearly hydro power production has been 128 TWh. In the same time period, the average import has been 8.0 TWh and the export has been 14.2 TWh[2]. For a country like Norway where nearly all power production is hydro power, the import/export situation is highly dependent on inflow to the magazines.

In 2010 the total hydro production in Norway was 117 TWh. The import was 14 TWh while total export was 7 TWh. Compared to a normal year, 2010 had a low production which resulted in the second highest yearly import of energy in Norway ever. Together with the low production, power prices in Norway were quite high in 2010. The average household power price in Norway in 2010 was 46.8 øre/kWh which was 11.6 øre/kWh higher than the previous year.

3.2 Credibility of the 2010 model

To check how accurate the 2010 model is, or rather how reliable the results are, we can compare the simulation results with historical production data provided by ENTSO-E. We first take a look at the hydro and wind production, see table (2). This analysis uses Norway as an example (area 1-5).

The magnitude of the numbers are in the same order, but there are clear differences in monthly production. This is visualized in figure (7).

The historical data show a production that has a peak in the winter months, as is natural. The simulated results follow no logical pattern and differs a lot from the historical data. To avoid disqualifying the credibility of the model based simply on these results it could be argued that

Table 2: Historical data provided by ENTSO-E.

	Historical ENTSO-E data		2010 simulation results	
Month	Hydro [GWh]	Wind [GWh]	Hydro [GWh]	Wind [GWh]
1	14 256	94	16 704	192
2	12 071	65	12 562	134
3	10 554	0	12 744	186
4	8 072	66	10 858	114
5	6 918	43	12 709	87
6	6 348	59	15 175	120
7	7 303	64	13 955	114
8	7 373	56	9 613	93
9	8 540	51	8 208	75
10	10 895	119	11 546	241
11	11 589	91	8 012	167
12	13 367	100	5 878	199
Total	117 286	808	137 965	1 720

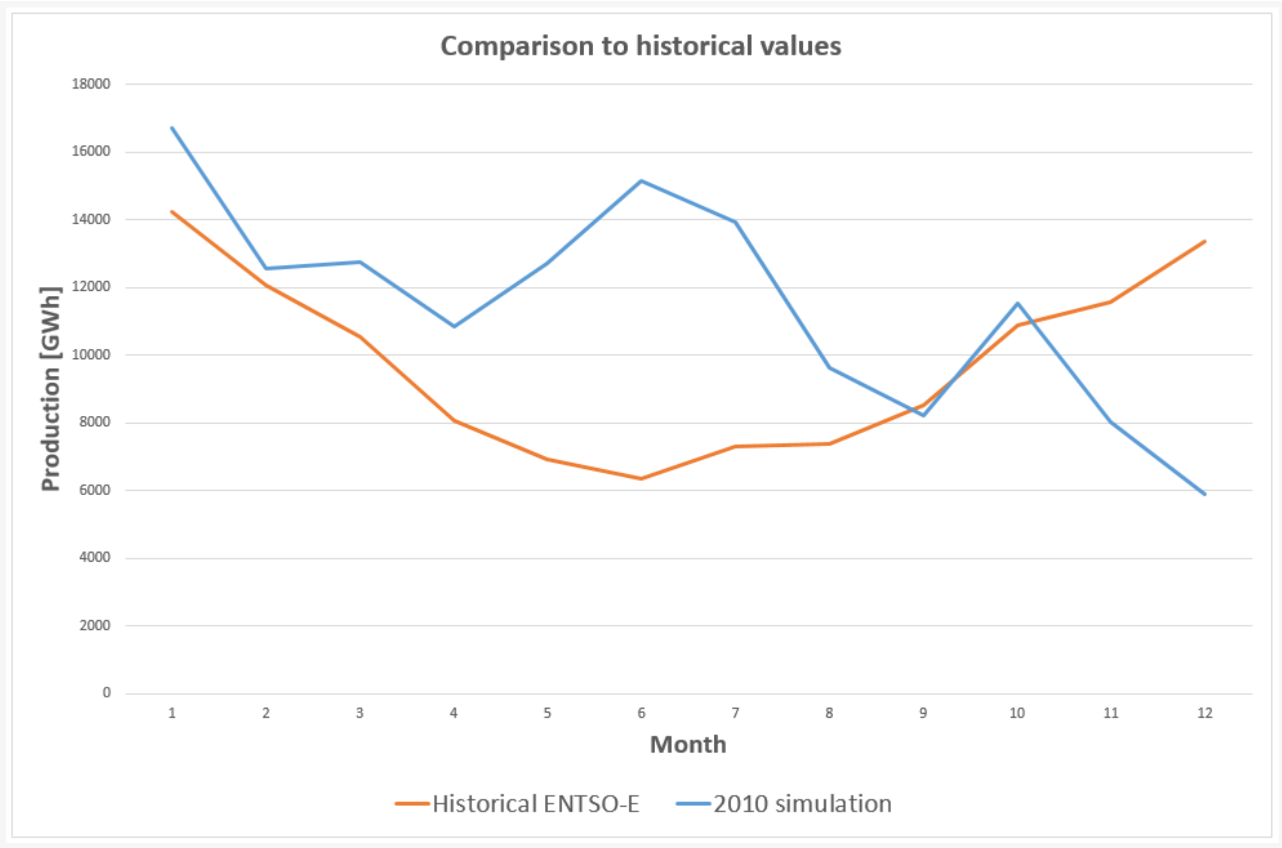


Figure 7: Historical and simulated hydro production numbers for Norway.

the production has to be simulated for several years and seen in a bigger picture.

Following this, it is now natural to look at the export/import situation in Norway, to check whether the export and import matches the difference between production and consumption. The results from the simulation is displayed as hourly power exchange between areas. To be able to get a clear picture of the exchange situation, it is necessary to collect the exchange data and display them for each area for a given time period, see table (3). Monthly values are used here.

Table 3: Table showing monthly exchange in Norway (area 1-5). Positive numbers indicate export.

Month	Historical ENTSO-E data [GWh]	2010 simulation results [GWh]
1	152	2 412
2	525	-194
3	1 296	-1 218
4	1 538	-202
5	1 791	3 202
6	1 455	6 726
7	-131	5 890
8	299	1 138
9	-139	-301
10	-620	1 674
11	570	-3 309
12	801	-6 139

Further analyses show that the increased production during the summer months is due to an increase in export, and not an increase in consumption in Norway. The exchange situation in 2010 compared to the simulated values is shown in figure (8).

3.3 Using a new model to simulate year 2010

In lack of reasonable results from the first simulation of the 2010 model, some other way of obtaining comparable simulation results must be found. This has been solved by using an updated, new model with the old model's input parameters. This way, by running the simulation for year 2019 only (which is the first year of the new model's running loop), we get results that are more reliable and can be used as a comparison basis for future simulations.

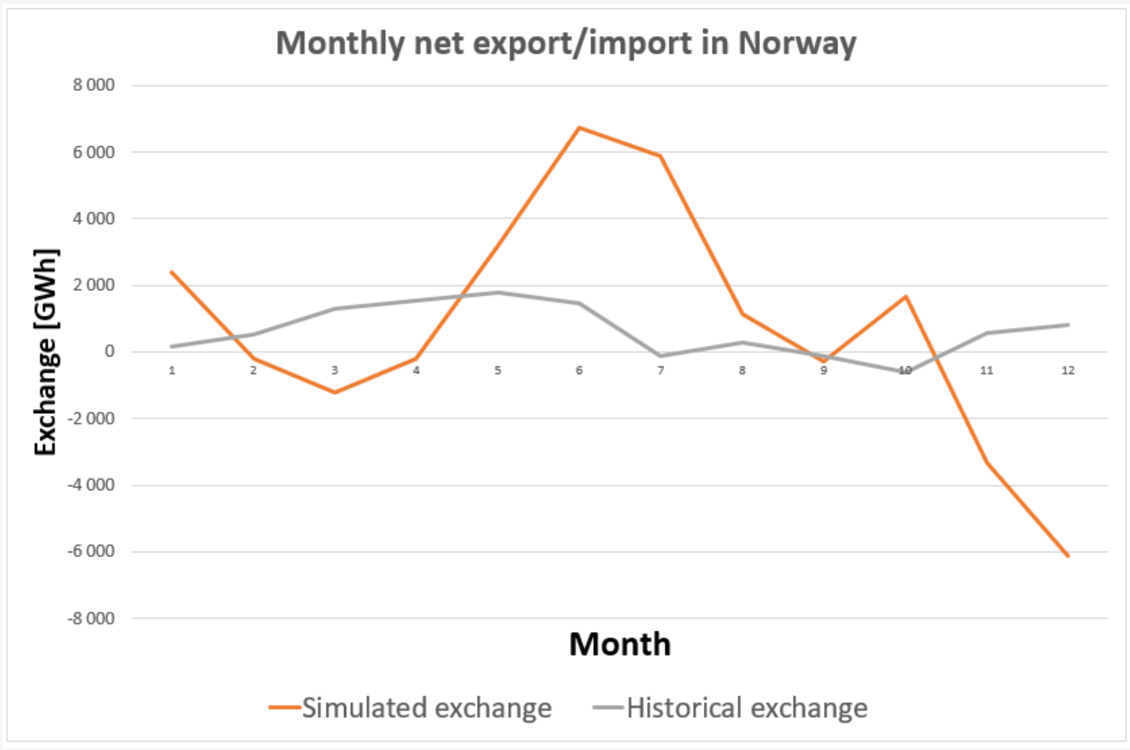


Figure 8: Historical values provided by ENTSO-E.

We can see from figure (9) that the correlation between the simulated production and the actual production in 2010 is much better than before, thus making the model results better match what we could expect. The simulated production is slightly higher, which has to be taken into account for future analyses. The load data that is used as input for the model shows that the total load in 2010 (2019) is 130 TWh, which partly explains why the modeled production is quite a bit higher than the historical production (which was 117 TWh in 2010). Lowering the input load data would presumably also lower the production, making the gap between the historical and modeled production much smaller.

3.4 Discussion historical model

While working with the 2030 and 2060 model, several changes to the models have been made. An electrification load bug has been fixed, which caused the load to increase each year and resulting in a power demand that was unrealistically high. The CO_2 prices have also been updated, allowing values to be changed depending on which scenario is simulated. The historical model was run prior to these changes, so any conclusions drawn from this model's results should be used carefully. Using the new historical model we got results that closely matched historical data, so it is clear that the model worked well for a single year simulation.

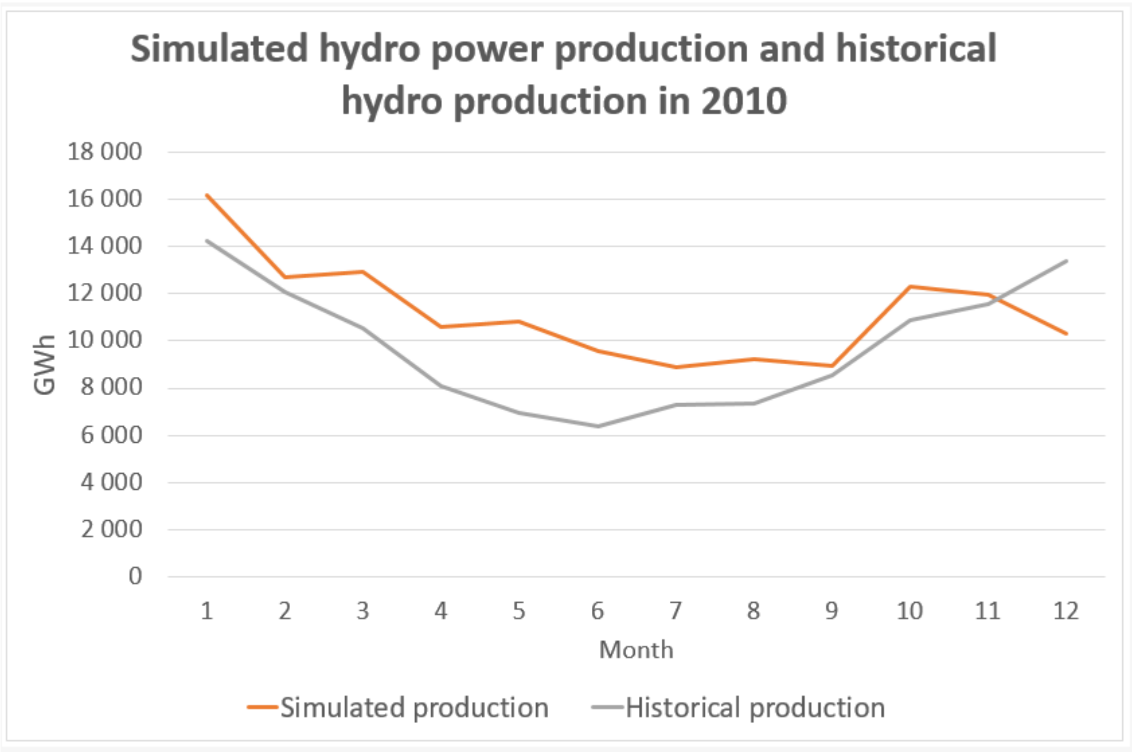


Figure 9: Simulated production and historical hydro power production in Norway in 2010.

4 Simulation to 2030

After establishing the results from the 2010 model, it is time to have a look at the results from the 2030 model. These results must then be evaluated based on the interpretation of the 2010 model results as well as compared with other analyses; NVE [1] and Statnett [13].

Areas of focus will be power production, power prices and exchange between areas. Key factors to keep in mind while looking at the results are among others: new transmission cables, exchange capacity and change in demand.

A power market analysis to 2030 made by NVE will be presented first, which will be one of the comparison basis' for the simulations. The other will be Statnett's marked analysis to 2040.

4.1 Power market analysis 2030 by NVE

This analysis is based on plans in 16 countries in Northwestern Europe.

Solar and wind power will be built in large scale, and is expected to partly replace thermal production. Figure (10) shows that solar and wind (light green line) can become bigger than nuclear power in 2030.

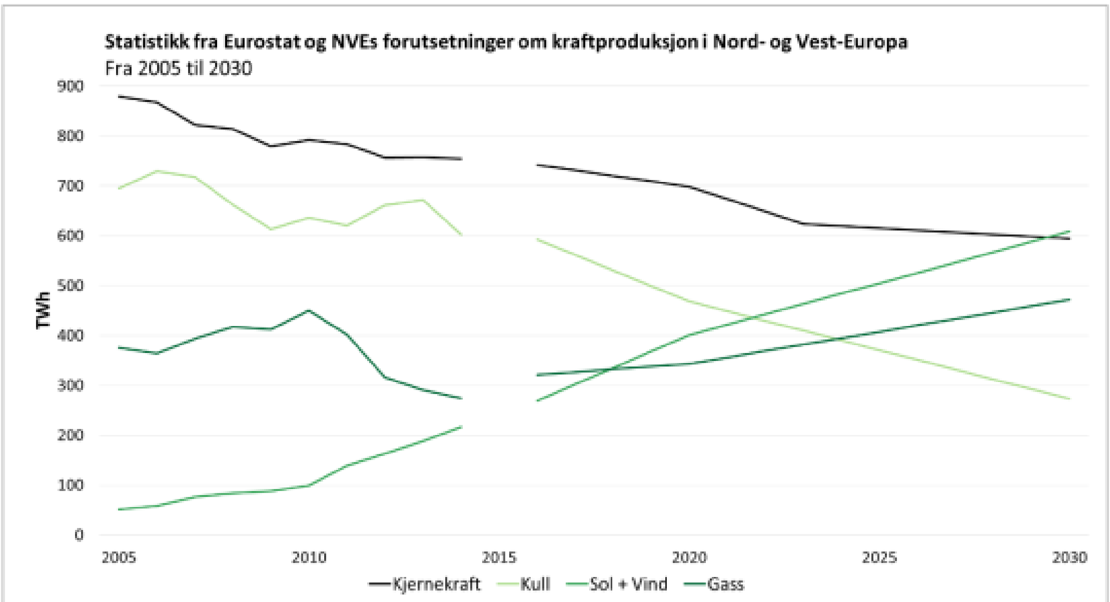


Figure 10: Historical production from 2005-2014 and NVEs simulation results. Credits to Statnett for the figure [1].

Power surplus in the Nordic countries will increase from 5 TWh in 2016 to 27 TWh in 2030.

This is due to installation of new renewable energy, which heavily outweighs phase-out of nuclear energy in Sweden and electrification of the transportation sector.

The transmission capacity in the Nordic countries is expected to multiply towards 2030, with several more cross-border transmission lines. The total capacity is expected to rise from today's 5000 MW to 14 000 MW in 2030. New transmission cables to Europe from Norway will lead to slightly higher power prices, as well as more variation in daily prices and less variation in seasonal prices. Cables to Germany and Great Britain will lead to an increase in the power price of 2 øre/kWh in 2030.

The most important factors for power prices in Norway is the price of CO_2 and fossil fuels. These prices impact Norwegian prices directly from the remaining thermal power plants in the Nordic countries, as well as through the transmission cables to Germany and Europe. NVE's analyses show that an increase in CO_2 prices of 1 €/tonne results in an increase of 0.4-1 NOK/kWh in Norway.

4.2 Case without electrification

This simulation assumes no electrification of offshore petroleum installations in the period 2019-2030.

4.2.1 Power prices

The power price results from this simulation are shown in figure (11).

This shows that prices in a4 and a5 will be mostly constant, declining slightly towards 2030. Prices in a1, a2 and a3 will greatly increase after 2026.

4.2.2 Power production

An easy way to check whether the power production is reasonable or not is to look at the yearly hydro power production. We expect a production that peaks during the winter months and reaches a low during the summer.

As seen in figure (12), the production profile matches what we could expect, except for the last month, where the production flats out and even declines.

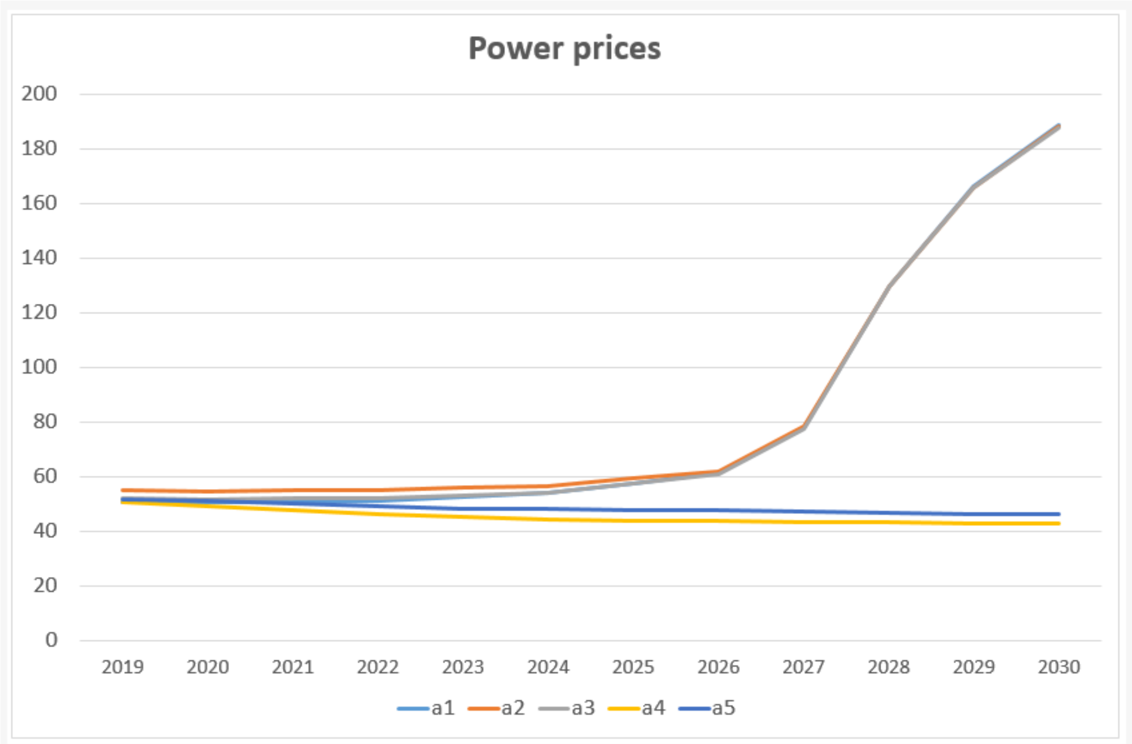


Figure 11: Power price simulation 2019-2030.

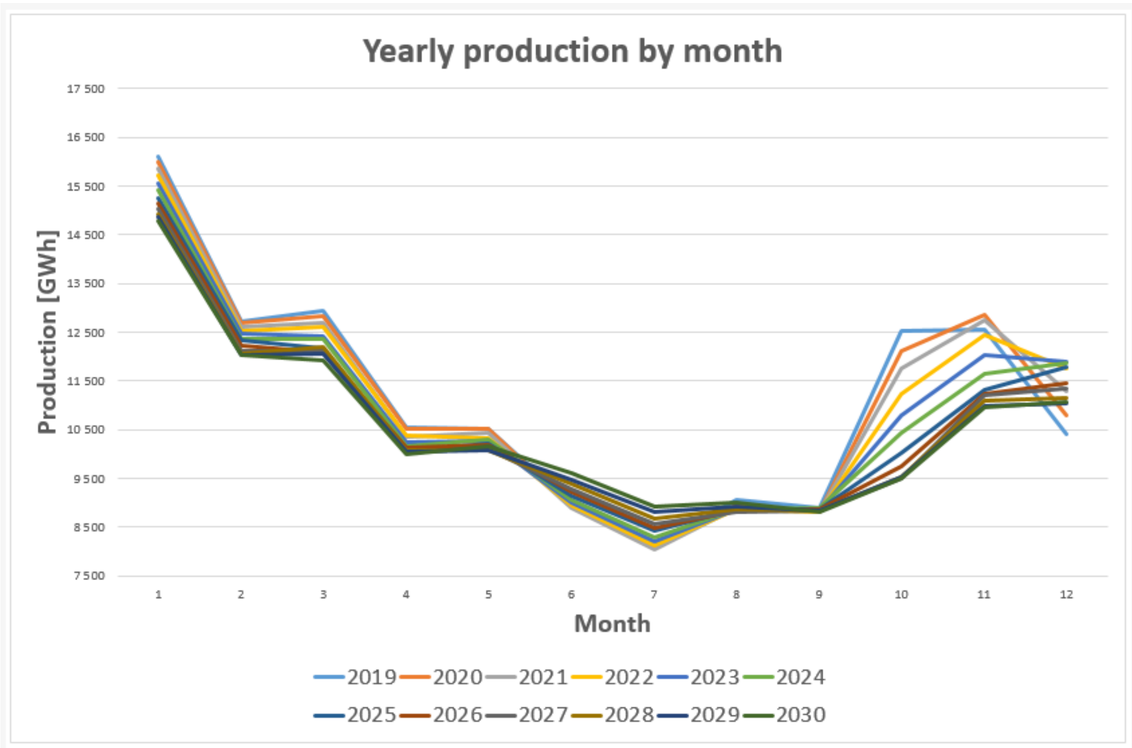


Figure 12: Hydro production in the period 2019-2030 as simulated.

4.2.3 Reservoir level

To work properly, the model should update reservoir levels correctly, meaning that the end value of one reservoir in one year should match the starting value of the next year. A graph showing the reservoir level in one unit is shown in figure (13).

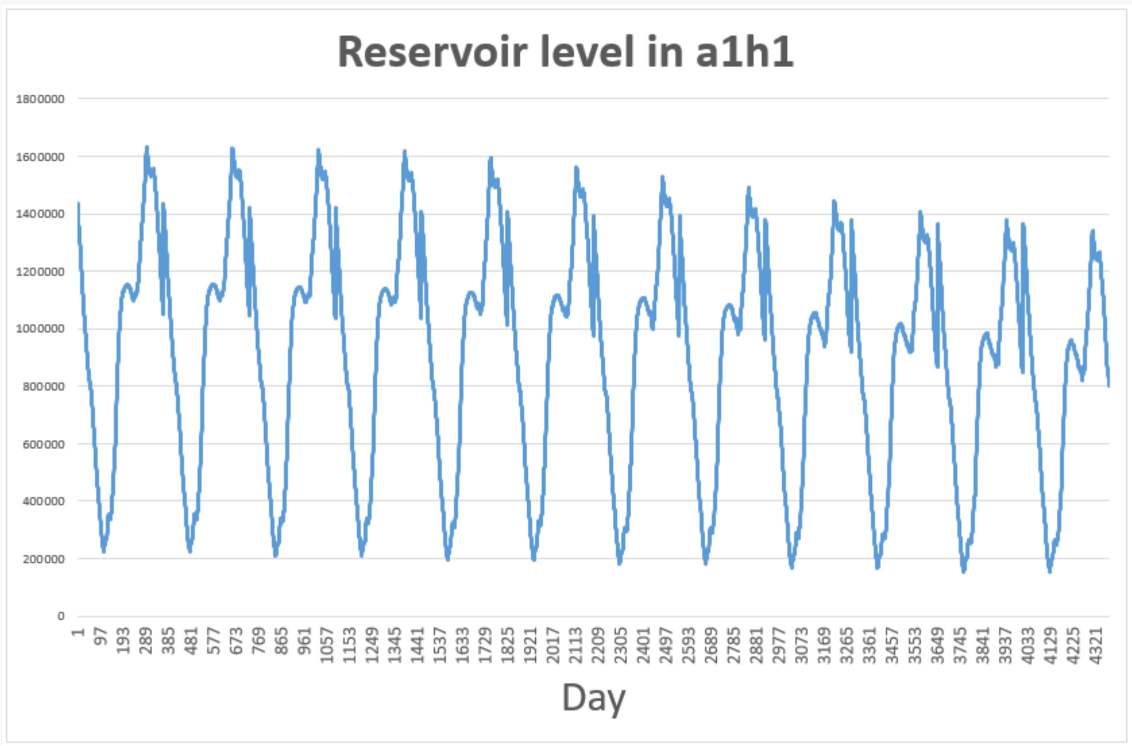


Figure 13: Reservoir level unit h1 in area a1 for the period 2019-2030.

The reservoir level does not follow the preceding year, as shown by the jump in reservoir level on the start of each year. It seems to follow the same pattern each year, which might be a result of hydro production always being at maximum production as well as the system load being unchanged from 2019 to 2030, meaning the general form of the graph will look equal each year.

4.3 Case with full electrification

The only difference between no electrification and full electrification is a varying load of up to about 300 MW extra in a1 (southern part of Norway). This load will simulate full electrification of Utsira. See figure (14) for a load profile of Utsira.

Power prices in the full electrification model are a lot higher than for no electrification. Seeing this together with the decreasing production of hydro power, it is clear that the increased demand will result in power production that is significantly more expensive than hydro production, thus the high power prices. Power prices in a1 for both cases are shown in figure (15).

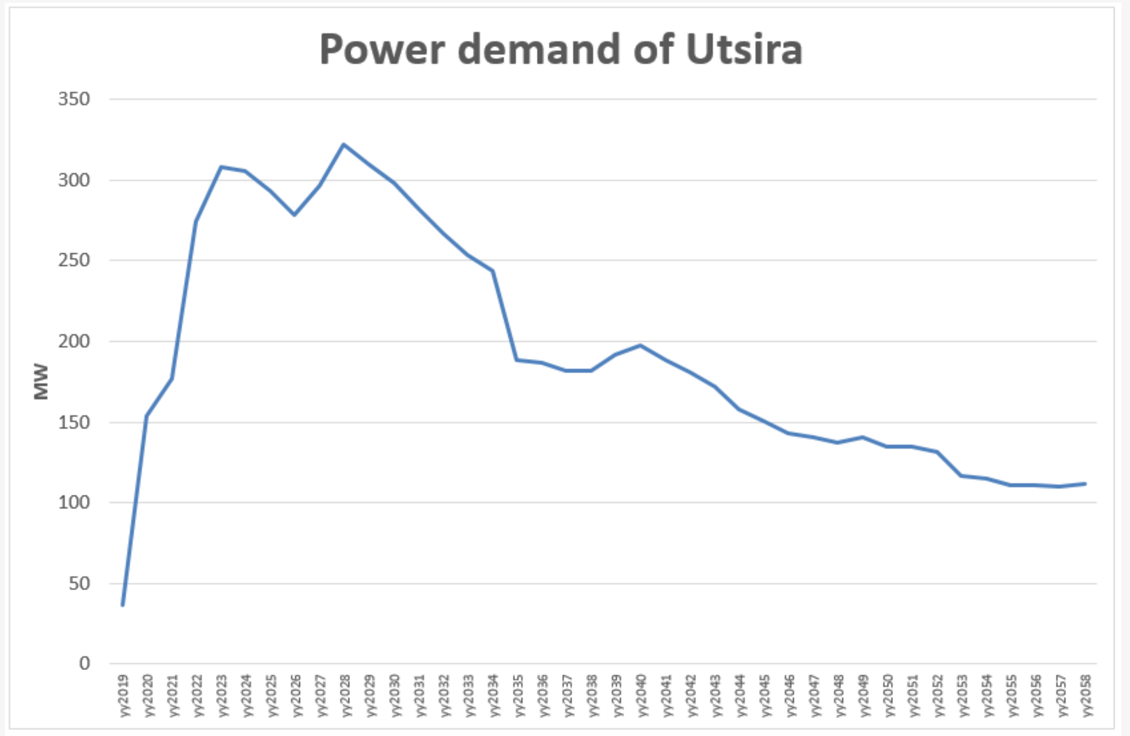


Figure 14: Yearly power demand of Utsira, which has to be supplied with power from shore.

With the increase in load in a1, Norway either has to produce more power, or import more. The exchange between Norway and Denmark is here used as an example (figure 16).

We see that with electrification, the net import has increased. Without electrification, Norway exports power during nearly 1700 hours in 2030, whereas with electrification, the amount of export hours has been reduced to 1100.

Hydro power production is also on a decline when full electrification is applied to the model. See figure (17).

4.4 Discussion 2030 model

After running the first simulation to 2030, a mistake in the input parameters was discovered. The NordLink cable, which connects a1 and a14 in our model, was not in use, and was corrected to function properly. Prior to correcting this mistake there was no flow on the cable.

After running the model with corrected values for the NordLink cable, the results were much as expected. Power prices in a1 and a14 were evened out slightly, as shown in figure (18).

With Utsira requiring more and more power, with a peak around 2028, it is expected that the

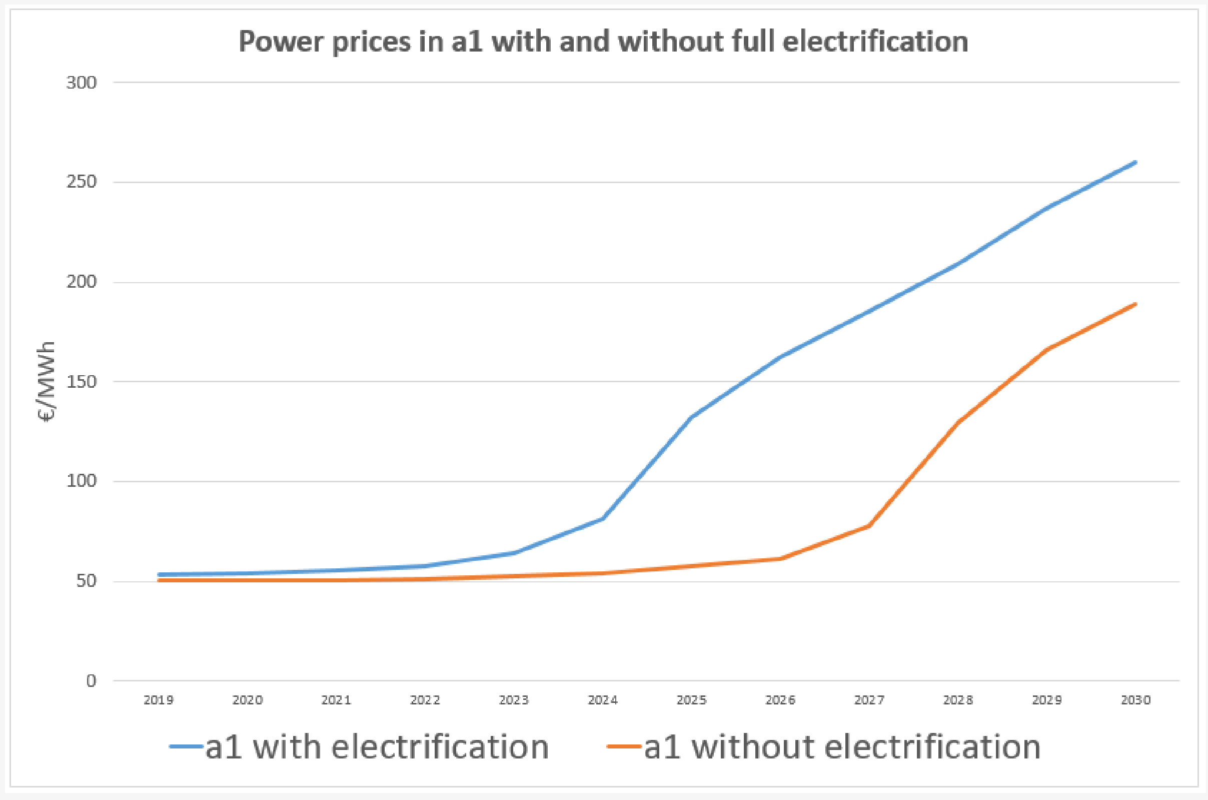


Figure 15: Power prices in a1 for no electrification and full electrifiation

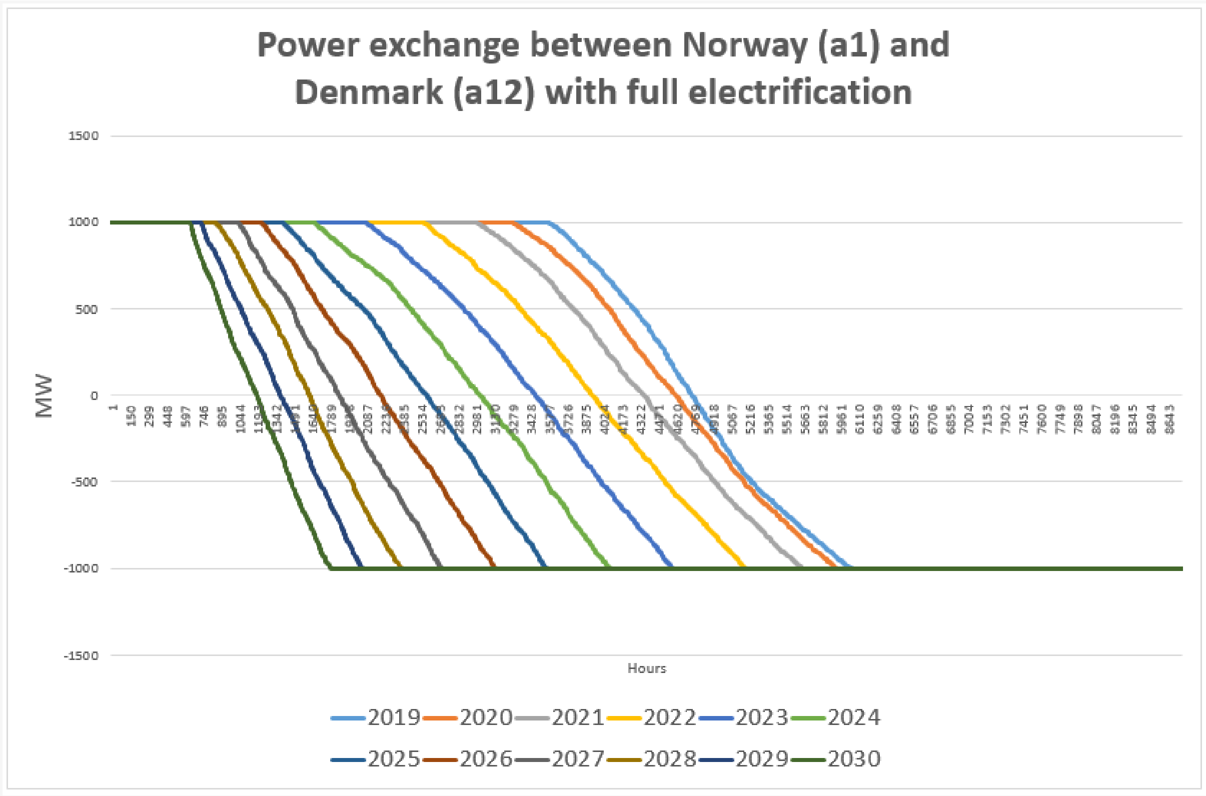
import to Norway (a1) will increase. Examining the exchange situation, wee see that the import indeed increases towards 2030 (figure 19).

As seen in the figure, the net export in 2021 is positive (1.55 TWh), whereas the net export in 2030 is negative (4.40 TWh import). The electrification load of Utsira in a1 results in a yearly increase of several TWh, so if Norway is not producing any more power in 2030 than what is the situation today, all of this has to be imported. The majority of this energy is supplied via the NordLink cable and the rest is divided between transmission lines and cables to Sweden, Denmark and the Netherlands.

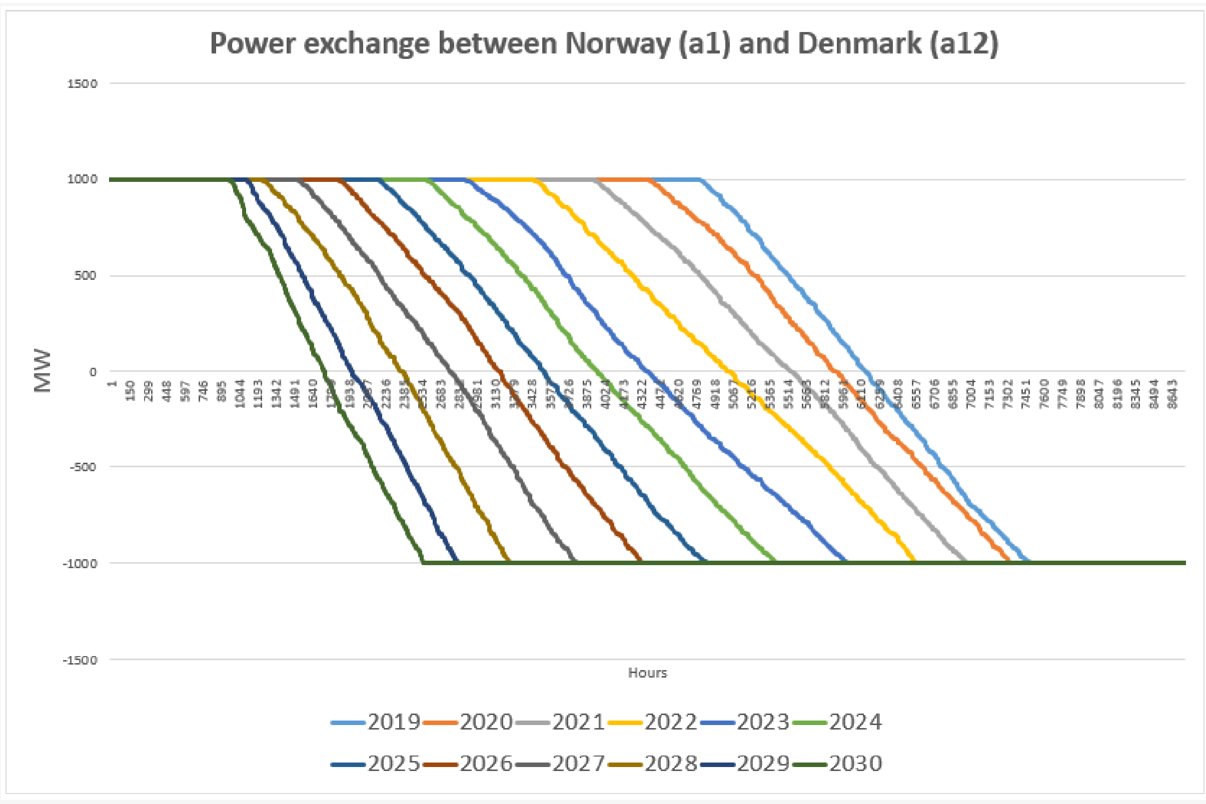
4.5 Comparison with NVE's analysis

For 2030, NVE's analysis show that solar and wind power combined could be larger than nuclear power production. Our results from the simulation, table (4), show that nuclear power production is still higher than solar and wind combined in 2030. Note that NVE's analysis includes several more countries than what our simulation does, so it is only natural that the results differ from each other.

Although the simulated solar and wind production doesn't exceed nuclear production in 2030,



(a) Exchange duration curve displaying the exchange between a1 and a12 with full electrification in a1.



(b) Exchange duration curve displaying the exchange between a1 and a12 with no electrification in a1.

Figure 16: Exchange on the NordLink cable for both the case with full electrification and no electrification.

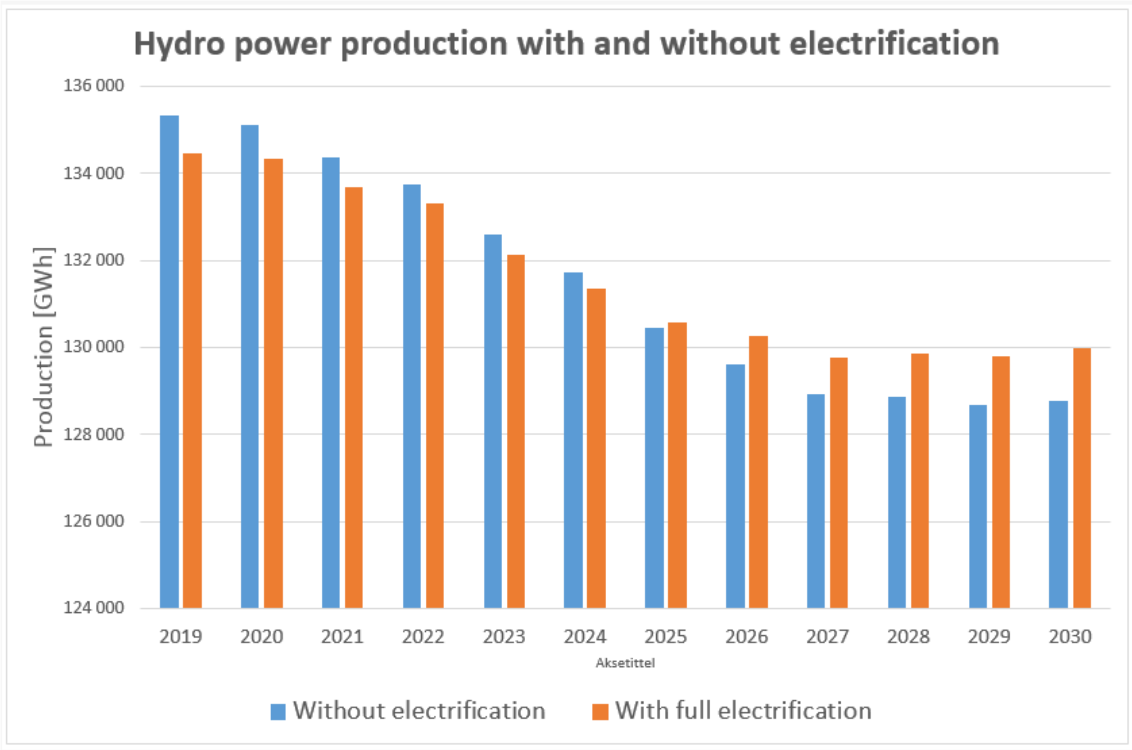


Figure 17: Hydro power production for both simulations; with and without electrification.

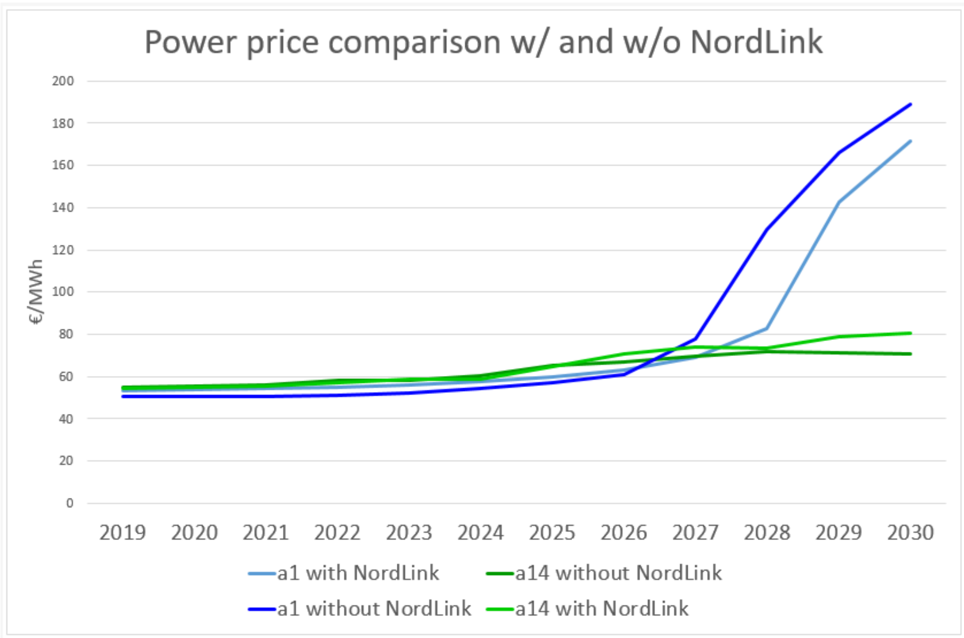


Figure 18: Power price in area a1 and a14 before and after NordLink is in operation. Note that this is WITH electrification.

Table 4: Table showing total power production in the system in 2030 for nuclear, wind and solar.

Year	**Nuclear**	**Solar**	**Wind**	**Solar + wind**
2030	260,6 TWh	28,8 TWh	211,5 TWh	240,3 TWh

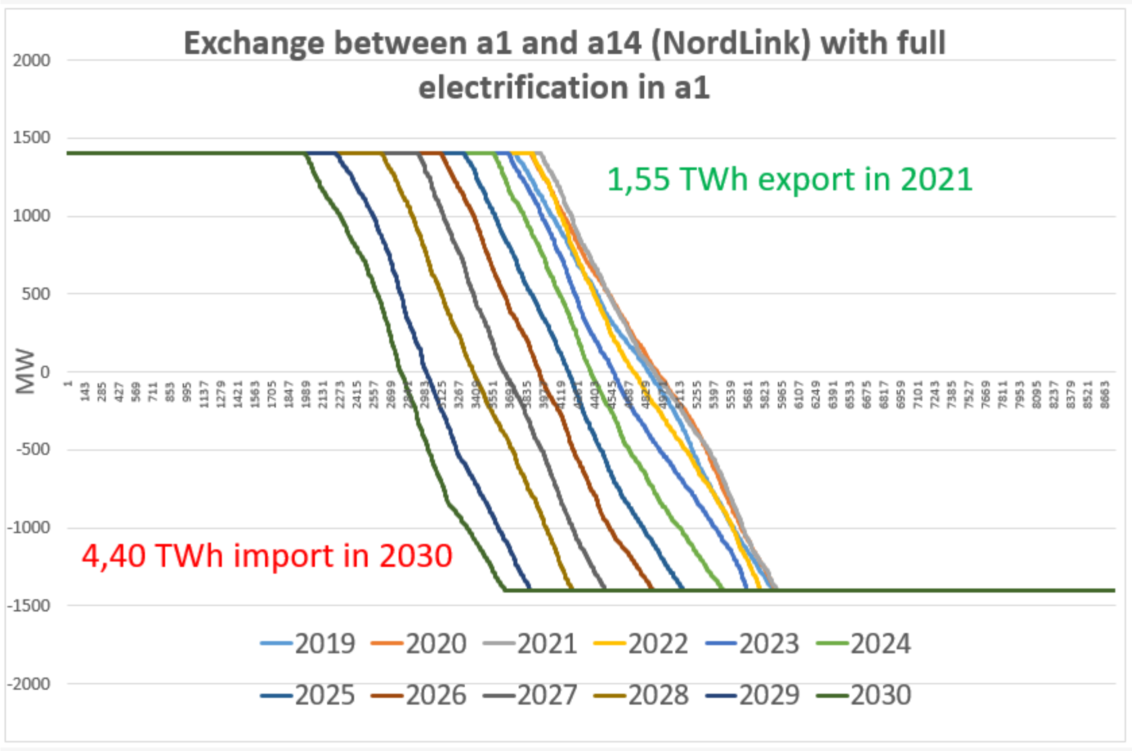


Figure 19: Ëxchange between a1 and 14 with full electrification.

the results indicate that it would in a few more years. See figure (20).

The simulated power prices does indeed increase towards 2030, but much more than we would expect and what is reasonable. Figure (18) shows that the NordLink cable to Germany will even out the prices in the connected areas, but the prices after 2026 are much higher than what will most likely be the case in 2030. The fact that the power price is increasing, however, is a good indication that the model is following the expected trend of the power price, despite the fact that it is too high.

4.6 Statnett's marked analysis

Statnett's marked analysis gives a detailed analysis based on simulations and power marked developments towards 2040. The simulated power prices in Southern Norway and Germany are shown in figure (21).

From the figure we see that the power prices in both Southern Norway and Germay rise steadily towards 2030, and decreases slightly from 2030 to 2040. The increase during the first 13 years is consistent with both NVE's results and our own model.

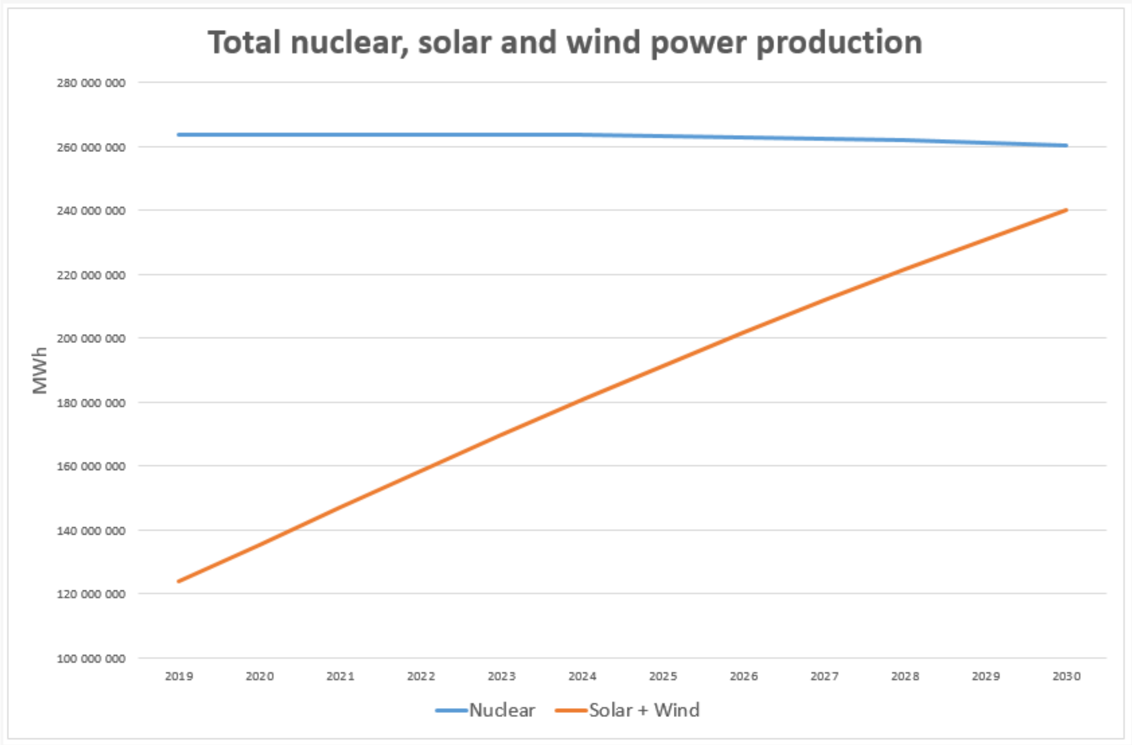


Figure 20: Solar and wind production increases towards 2030, nearly exceeding total nuclear production.

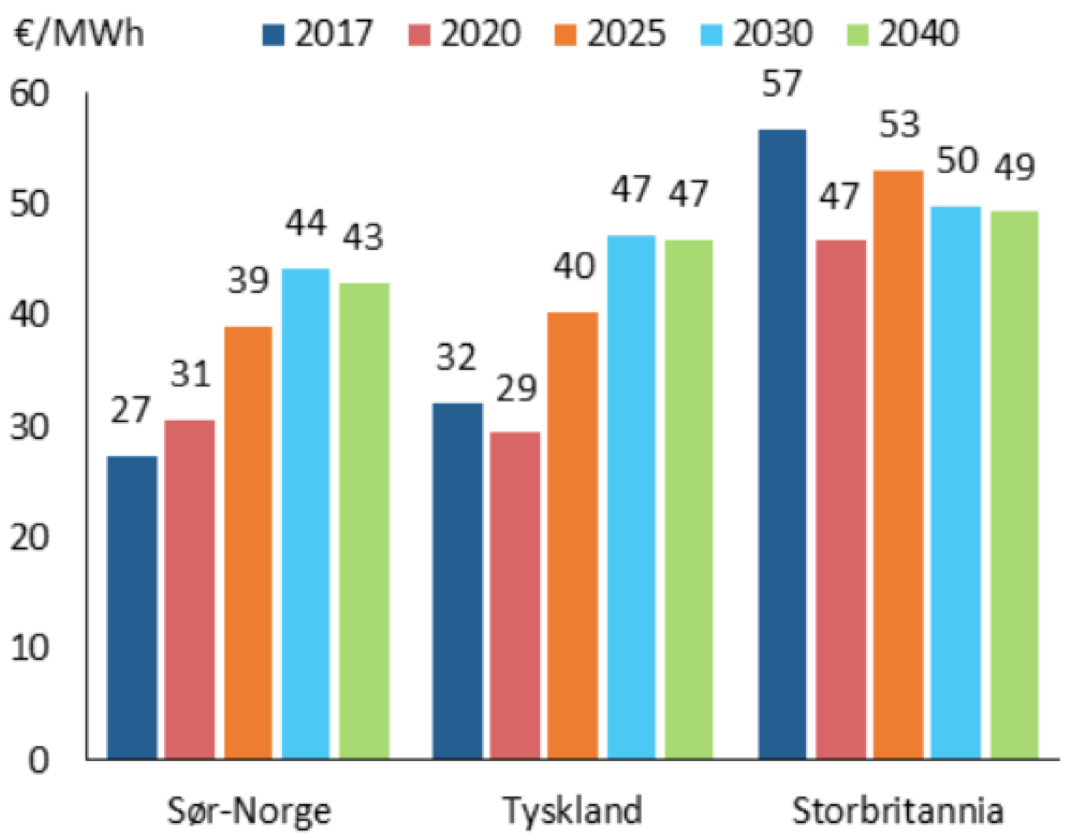


Figure 21: Statnett's simulated power prices in the Nordic countries towards 2040.

5 Simulation to 2060

When starting the first simulations to 2060, it became clear that the simulations would take too long. Simulating the period 2031-2060 would take nearly 48 hours.

Conveniently, another version of the model had been made in the meantime, making simulations to 2060 much easier. Time steps of 5 years was now used instead, meaning the code now had eight iterations (2020-2055) instead of 40 (2019-2058). This of course means that the model will be less detailed and have less calculation points, but it is a nice way of confirming the model is working as it should.

5.1 Power production

The simulations to 2055 has been done for both with and without emission costs. Both simulations include full electrification.

When analyzing the results it is interesting to look at both renewable and thermal production. Emission costs should have a large impact on thermal power production, thus increasing the production from renewable sources.

Gas and hard coal power production is shown in figures (22) and (23), respectively. We first look at what will happen when there are no emission costs. Gas power production will be quite low and decrease towards 2055. With no emission costs, hard coal power production will be very high during the first years, decreasing slightly every five years. The difference in production between gas and hard coal is easily explained by the fact that hard coal emits more than twice as much CO_2 as gas, and has lower production costs than gas[12].

With emission costs, the graphs show quite the opposite. Hard coal power production is reduced greatly while gas power production increases. Again, this is due to the high emission factor of hard coal, making the emission costs too high for hard coal production to be economically feasible.

Hydro production, figure (24), will decrease slightly in Norway (notice the y-axis starts at 90 TWh). This is more or less only a consequence of the increased installed wind power capacity in the system, see figure (25). The nature of wind power, needing to be consumed at the same time as it is produced, allows the water to stay in the magazines.

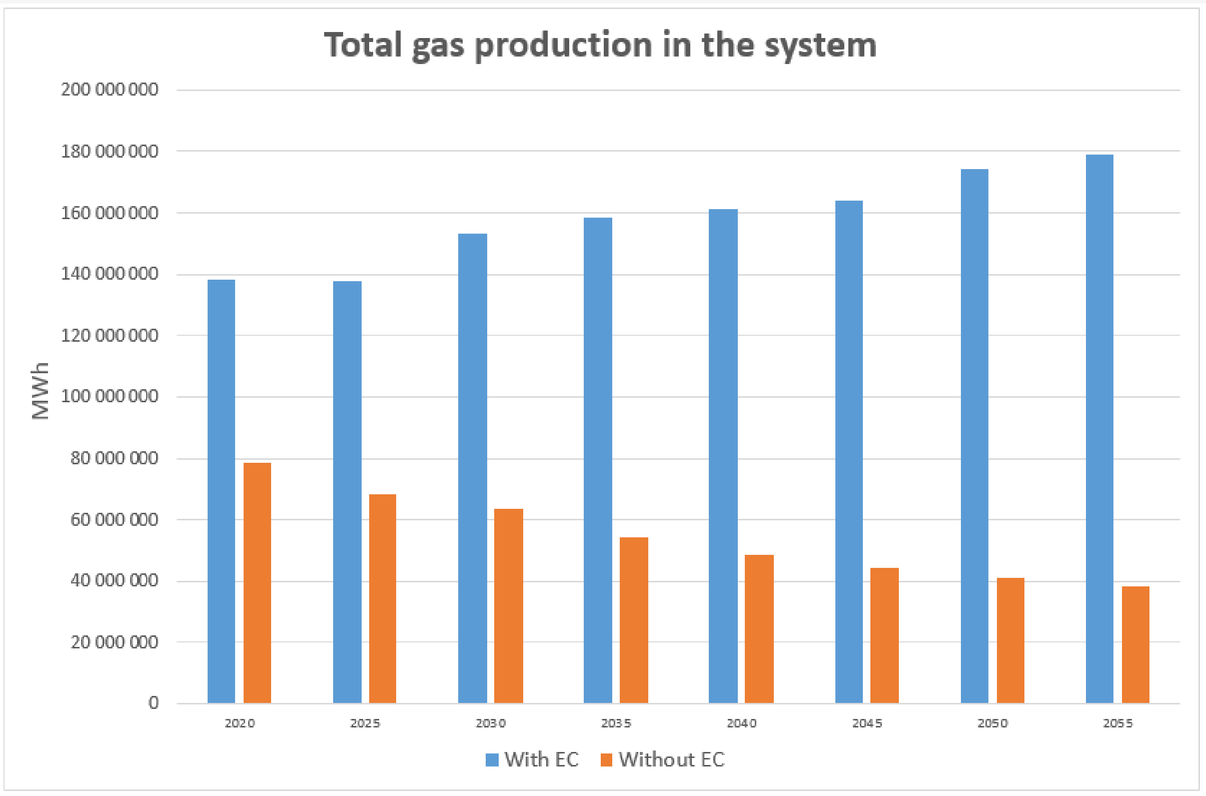


Figure 22: Gas power production towards 2055 with and without emission costs.

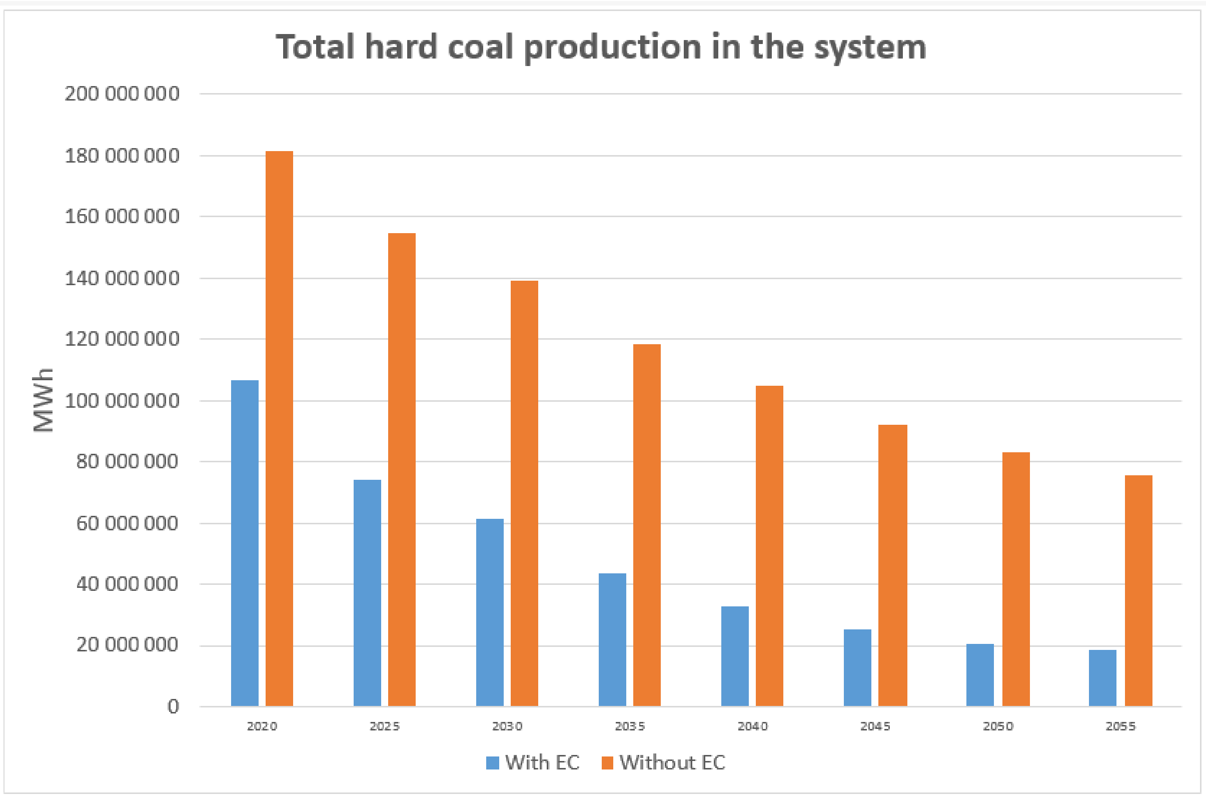


Figure 23: Hard coal production with and without emission costs.

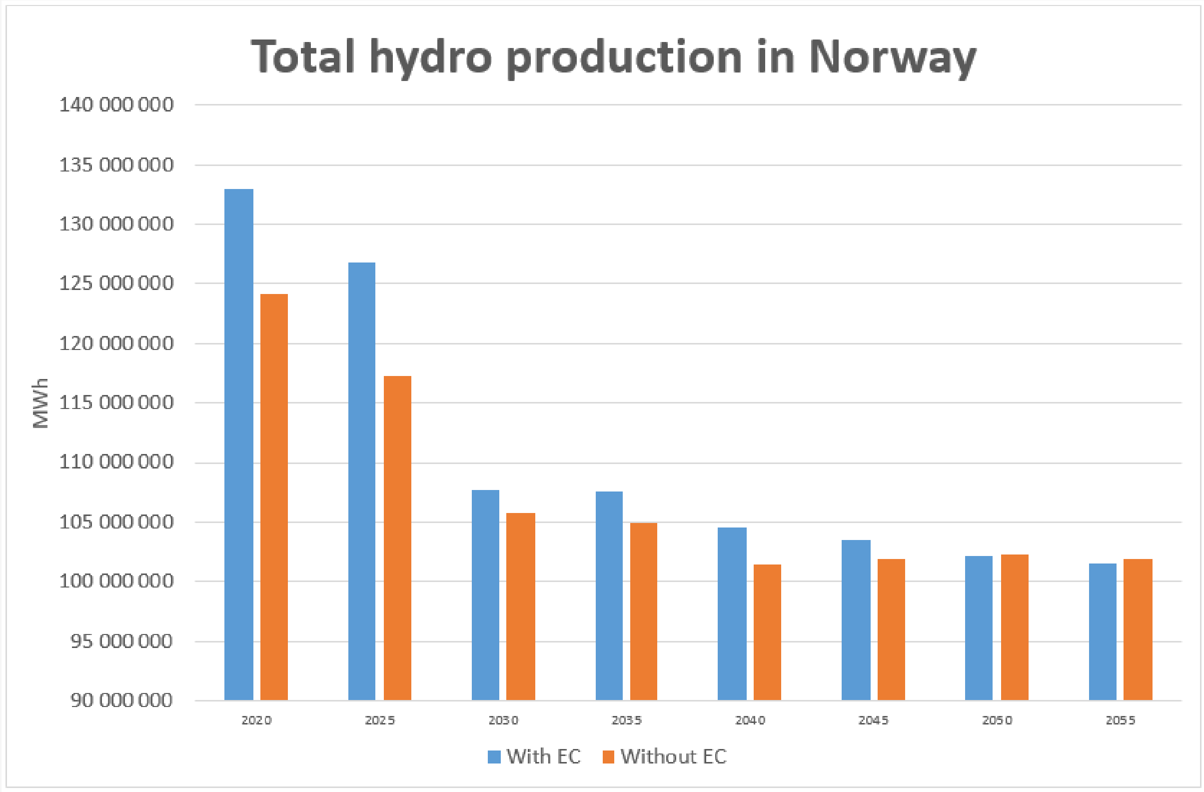


Figure 24: Hydro production with and without emission costs.

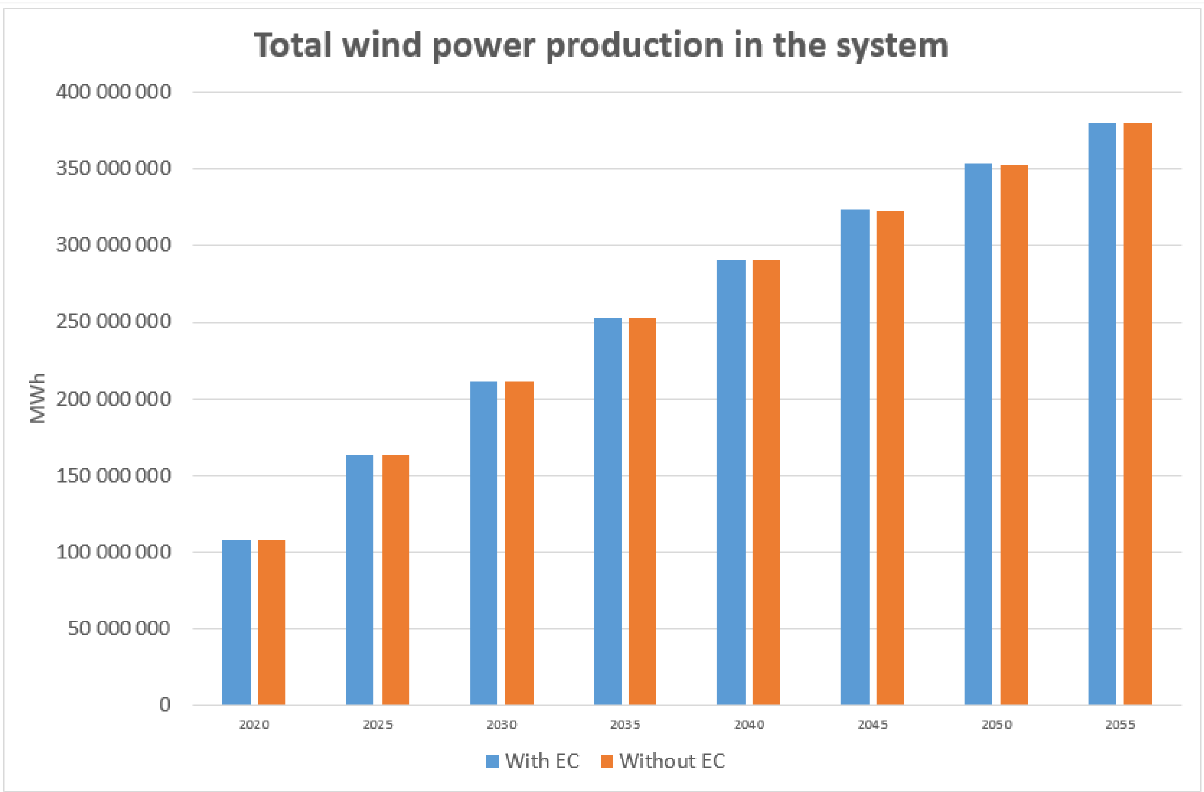


Figure 25: Wind power production with and without emission costs.

5.2 Reservoir level

The simulated reservoir level is now working better with the updated model. The level is updated correctly for each year, not starting at the same value each year as the results showed earlier. There is, however, an inconsistency between the first and second iteration, where the reservoir level does a jump to the start of the second iteration.

We see that the total reservoir level in the system, figure (26), increases towards 2055. With the increased installed wind capacity and thus lower hydro power production, hydro reservoirs will see an increase. In the long run, this can lead to more spillage and waste of resources, so in a perfect situation the load in the system would have to increase in a way that allows hydro power to be used.

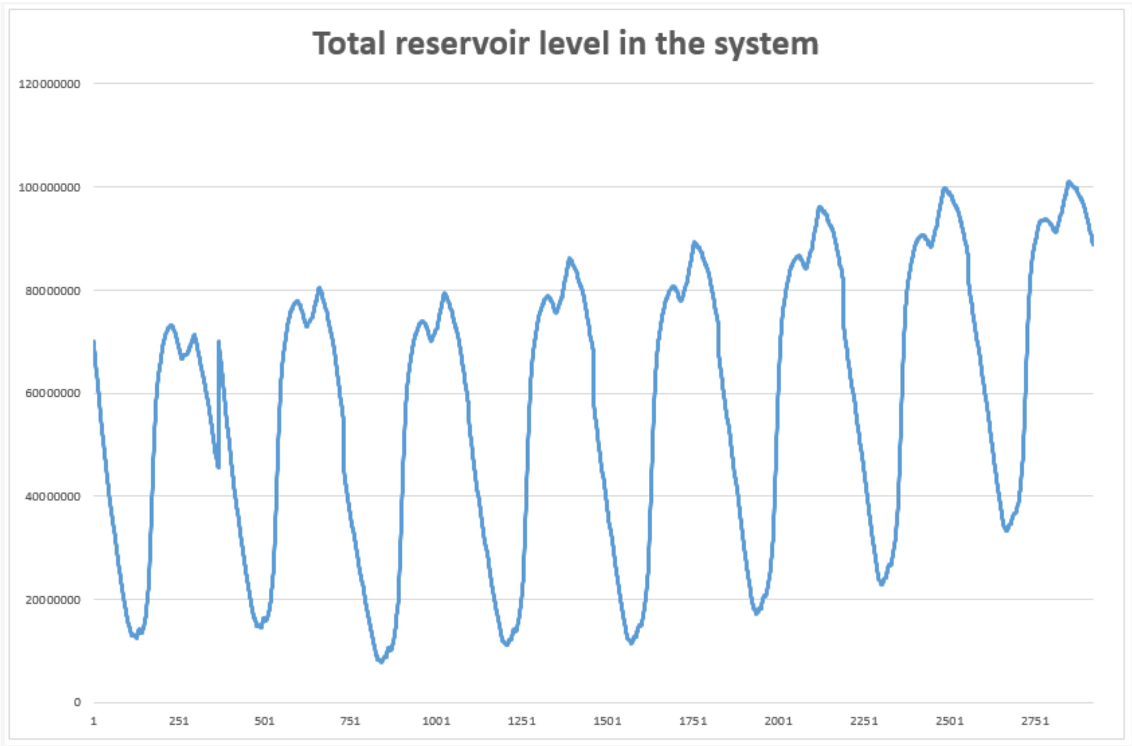


Figure 26: Reservoir level in the system for the entire simulation period.

5.3 Power prices

The power prices are much higher when emission costs are included, see figure (27) and (28).

These results were obtained before the aforementioned electrification bug was fixed. This means that the power demand has increased every year with the current year's electrification demand. The bug is explained below.

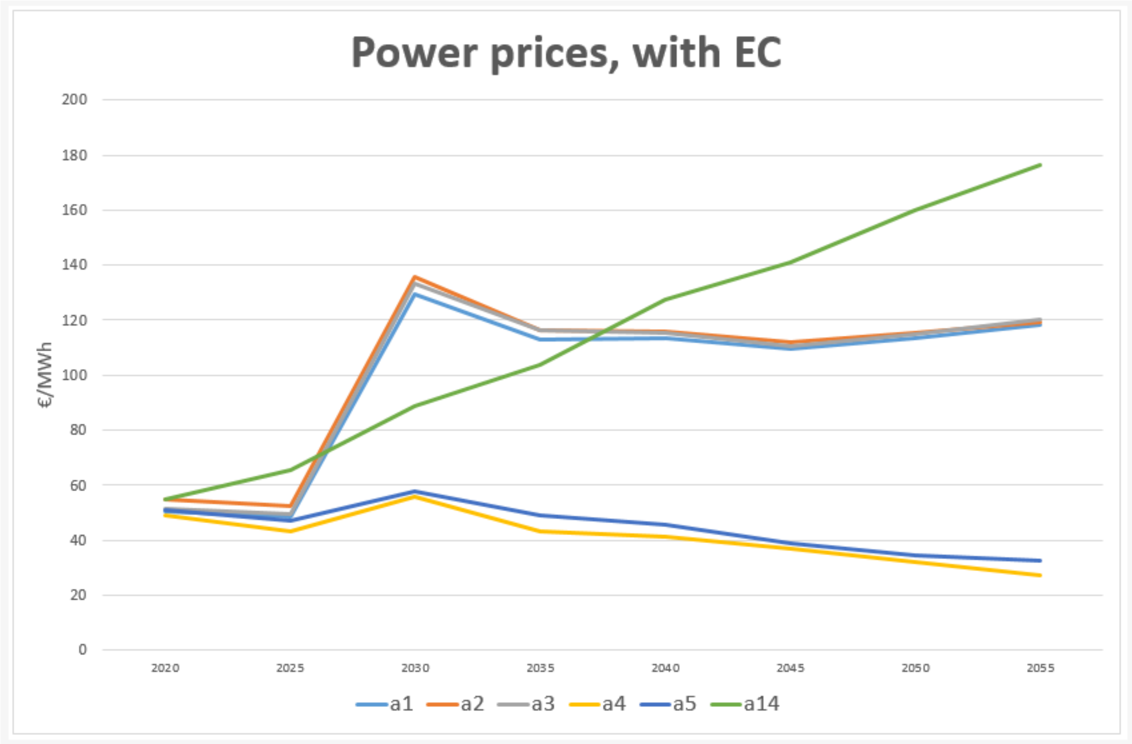


Figure 27: Power prices in Norway and Germany (a14) with emission costs.

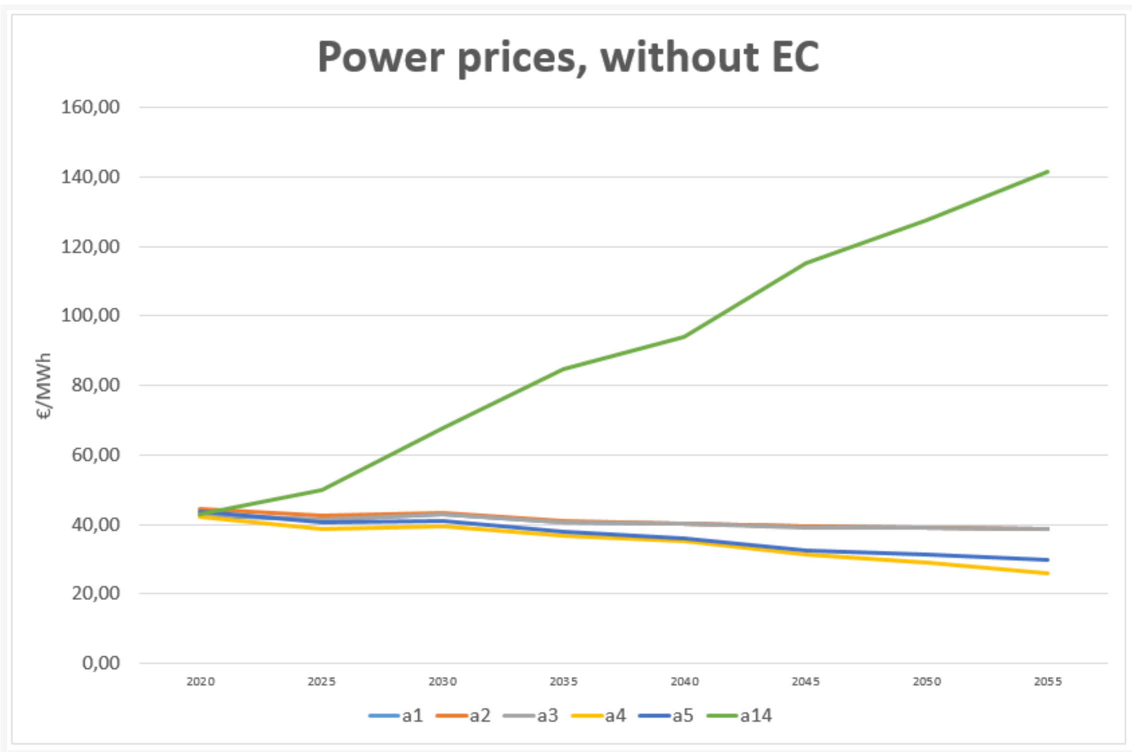


Figure 28: Power prices in Norway and Germany (a14) without emission costs.

```
loop(YY1,

Load('a1',tau,t) = Load('a1',tau,t)+ demand(YY1,'Power');

);
```

The intention of this line is to add the electrification load to the power demand each year. Writing it this way will result in year i having a load of the base load plus every year's electrification demand before year i. The total load in a1 with and without the bug is shown in figure (29).

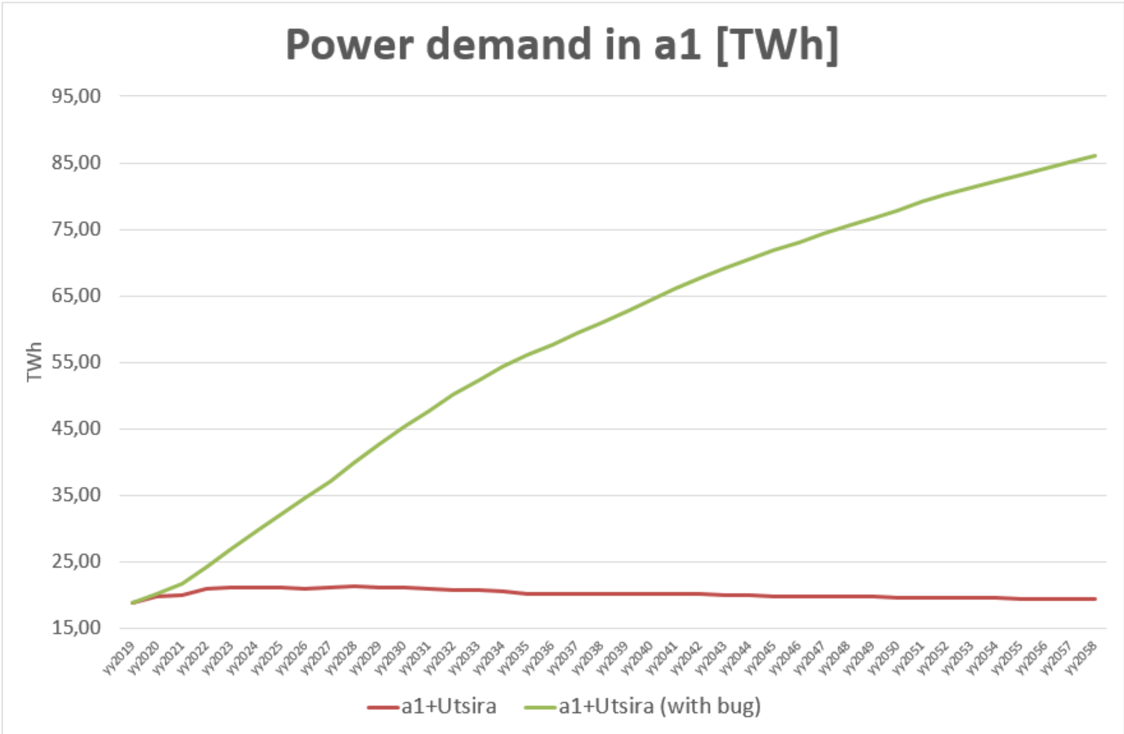


Figure 29: Total power demand in a1 with and without the electrification bug.

Increasing the load will increase the use of high emitting power production. It is likely that this is the reason why the power prices are so much higher when we include emission costs. Running the simulation after fixing the bug would presumably result in significantly lower power prices.

5.4 Power prices after bug fix

After fixing the bug and running the simulations again, the power prices turned out as shown below in figure (30).

As expected, now that the load is reduced in a1, prices in a1 and connected areas are reduced drastically compared to the previous case (figure 27). The spike around year 2030 is most likely a result of the power demand of Utsira reaching a peak at this time, see figure (14).

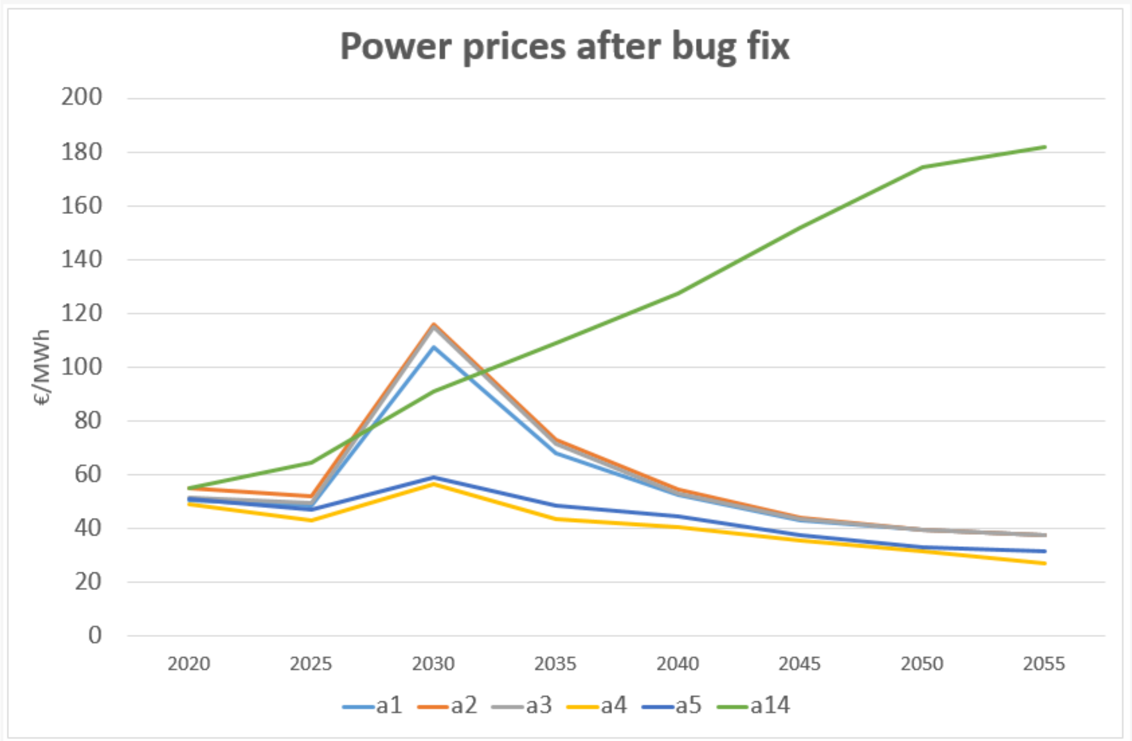


Figure 30: Power prices in Norway + Germany after the bug fix.

5.5 Emissions

CO_2 emissions is the foundation for electrification and is what drives much of the development in most industries today. All the Nordic countries have ambitious climate goals, with the ultimate goal of being carbon neutral. For Norway, the aim is to be carbon neutral by 2050. With the current wind and solar power parameters as input to the model, it is interesting to look at the total emissions in the system. Figure (31) shows emissions in tonnes of CO_2 towards 2055.

The analysis shows that the emissions in 2055 will be near one third of what they are today.

To analyze the emission situation further, simulations for all the three scenarios described in the Theory section has been done. Results in figure (32).

We see that the "new policies" scenario, which is the base case in WEO 2016, follows the same pattern as the "current policies" scenario, with slightly lower emissions. The "450" scenario, which represents the scenario where global temperature increase is limited to 2°C, has significantly lower emissions, especially during the first 20-25 years.

Furthermore we look at the emission from each type of power industry, figure (33).

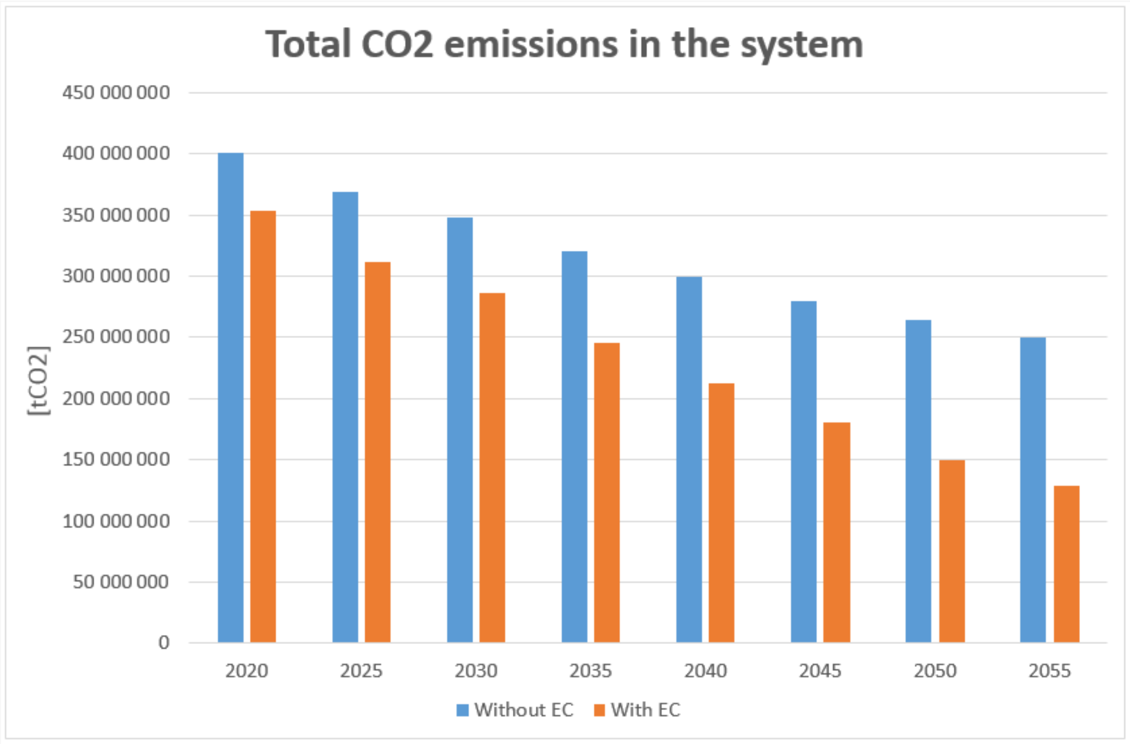


Figure 31: CO_2 emissions in the system for both the case with emission costs, and without.

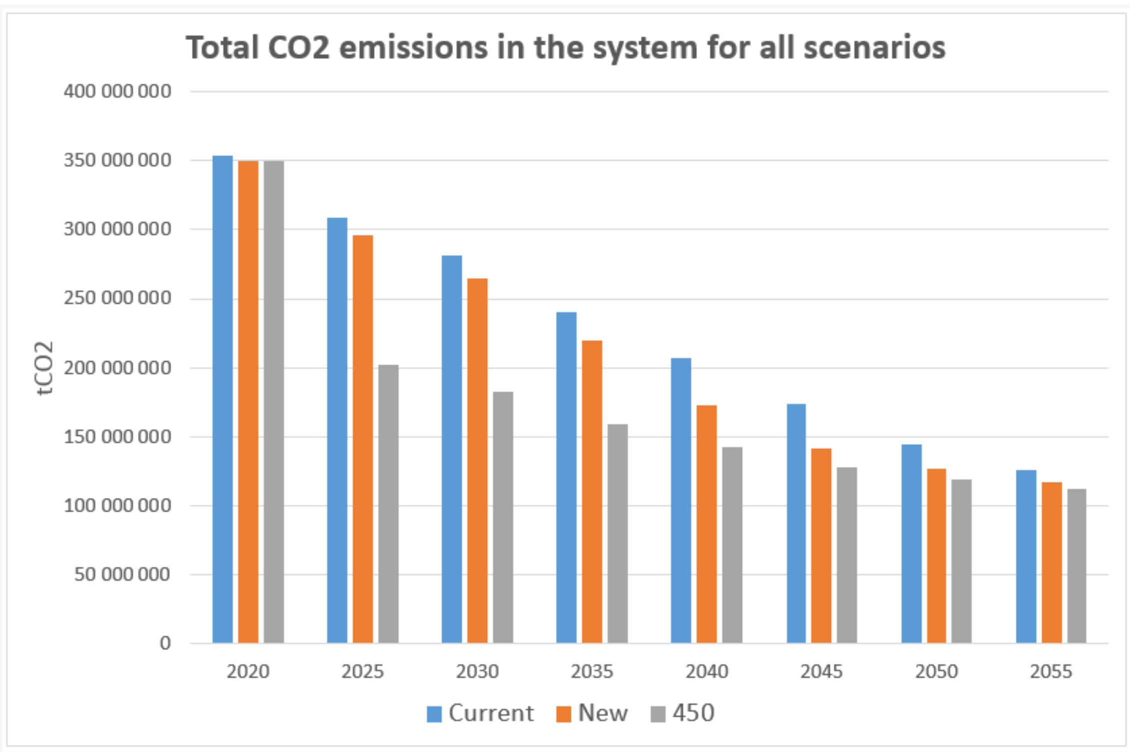


Figure 32: Total CO_2 emissions for the three scenarios.

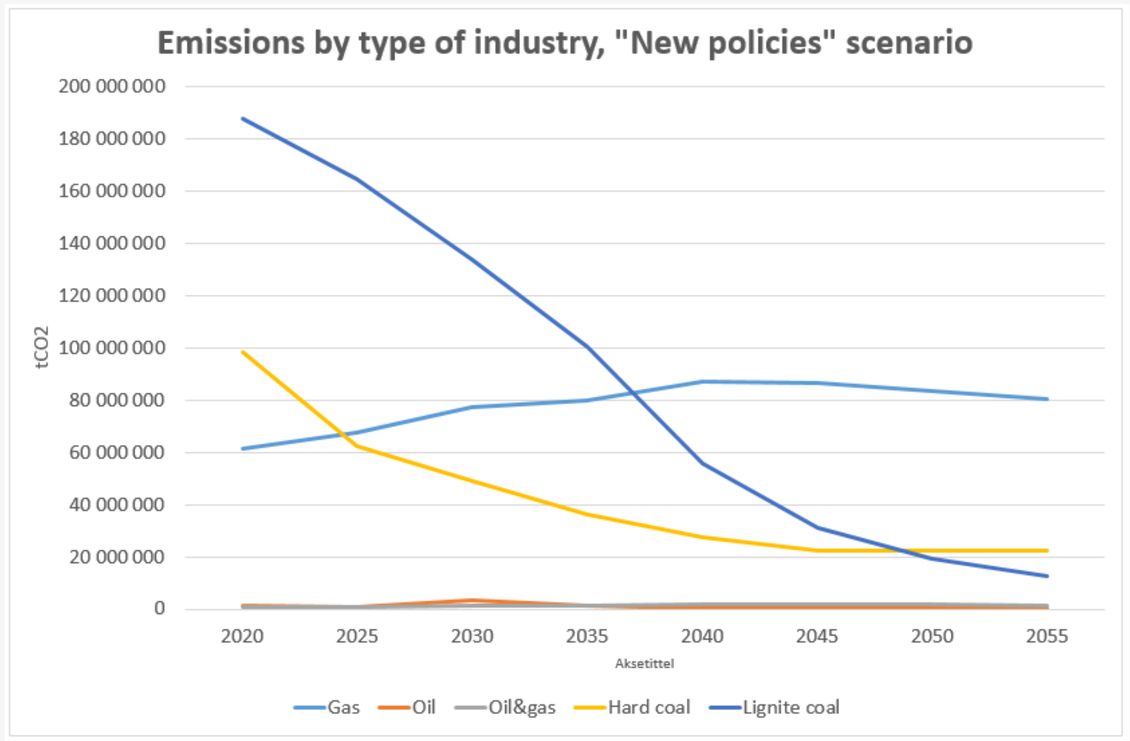


Figure 33: Emissions from each type of power industry with the "New policies" scenario. Emissions in tonnes of CO_2.

We see that the emissions from lignite coal experiences the biggest change; dropping from nearly 200 million tonnes of CO_2 in 2020, to 20 million tonnes in 2055. Emissions from gas power industry increases slightly, but as described earlier the total emission is reduced greatly.

5.5.1 Quantification of CO_2 emissions related to electrification

To quantify the CO_2 emissions related to electrification, a simulation where the electrification load in a1 is taken away has been done. Comparing the results from this simulation with a simulation where the electrification load is included should show the impact of electrification on emissions, power production and power prices.

CO_2 emissions from all industries for the case without electrification is shown in figure (34).

The visual differences between figure (33) and (34) are small and hard to spot, but it turns out that the total difference between the two scenarios is 63.2 million tonnes of CO2. The distribution of the emission difference between the two scenarios is shown in table (5).
We see from table (5) that the biggest change in emissions is in the lignite coal production. The total difference between emissions in the scenarios with and without electrification is 63.2 million tonnes, which is the sum of the differences in table (5).

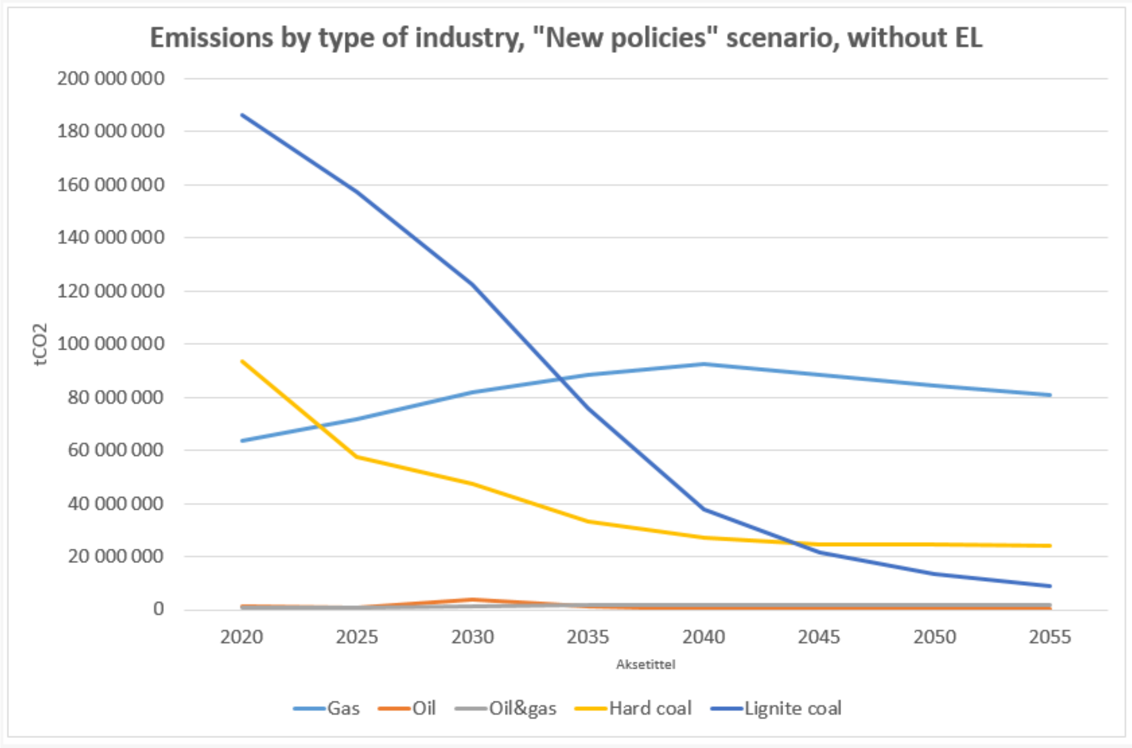


Figure 34: Emissions by type of industry, "New policies" scenario. Without electrification.

Table 5: Difference between the simulation with electrification and the simulation without electrification. All numbers in tonnes of CO_2.

	Gas	Oil	Oil and gas	Hard coal	Lignite
2020	-1 943 537	-45 408	-49 302	5 224 943	1 400 890
2025	-3 875 092	-38 186	-92 210	4 648 979	7 139 319
2030	-4 420 089	-166 889	-211 938	2 037 691	11 821 368
2035	-8 508 840	18 825	-147 116	3 018 693	24 721 248
2040	-5 153 426	130 341	-159 969	275 581	18 229 830
2045	-1 720 613	-4 168	-17 194	-2 324 887	9 193 336
2050	-853 058	-20 664	-6 956	-2 179 620	5 677 852
2055	-494 645	-24 401	-3 562	-1 607 414	3 722 187

5.6 Discussion and last simulations of the 2060 model

Consistent with the 2030 model, power prices towards 2055 keep rising in certain areas. However, some areas seem to have decreasing power prices, which is in conflict with both NVE's and Statnett's analyses. One factor that can explain the decrease in power prices is the massive investment in wind power. With zero production costs, wind power is a lot cheaper than e.g. gas and coal production. Our simulated coal production is decreasing towards 2055, whereas gas is slightly increasing. The simulated wind power production triples from 2020 to 2055, and should therefore contribute to the lower power prices.

Compared with the 2030 results, the reservoir level is much more reliable. The level updates correctly (except for the first iteration), and indicates that the model is working properly.

The results of the 2060 model presented in this section is based on CO_2 prices in the WEO 2016 "Current policies" scenario. The code has later been updated to include an option to use three different scenarios for CO_2 prices (see figure (6)), in which every scenario will produce different results from our model. E.g. the "New policies" scenario operates with slightly higher CO_2 prices, which will result in a bigger difference between coal and gas production. Higher CO_2 prices will favor low-emitting power industry, which in our case is renewable energy and gas. An example is shown in figure (35), where total gas production is shown for each scenario.

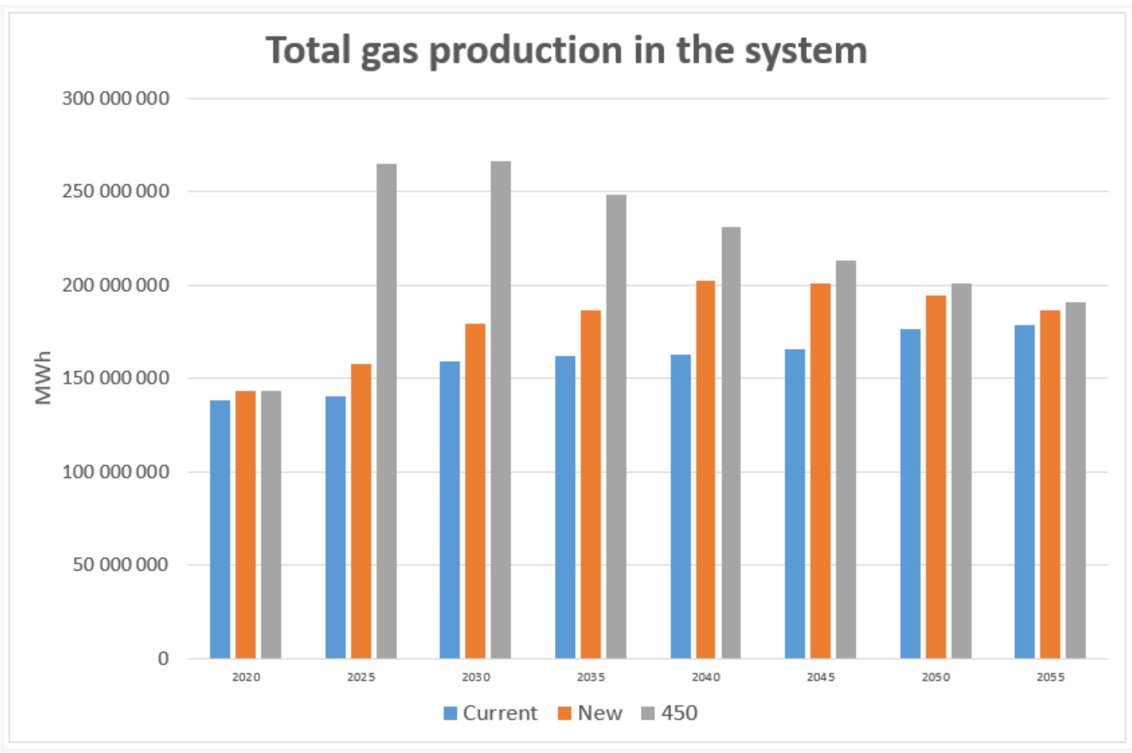


Figure 35: Total gas production in the system for each scenario.

From the comparison between the simulation with and without electrification, the total difference in CO_2 emissions was calculated to be 63.2 million tonnes over the 35 year time period. This number looks oddly high, as the increase in power demand in a1 is just a little more than 13 TWh, see table (6).

Table 6: Power demand of Utsira. This should be the only extra load in the simulation with electrification.

	El. power demand [MW]	**Total yearly energy demand [MWh]**
2020	153	1 346 509
2025	293	2 569 511
2030	298	2 610 687
2035	188	1 654 282
2040	197	1 731 225
2045	150	1 317 655
2050	135	1 183 004
2055	110	971 410
	Total	13 384 282

If we assume that all this extra energy is produced in the most emission intensive way, lignite coal production, we can calculate the maximum emission change from 13.3 TWh extra production.

$$e_{CO2} = 13,384,282 \text{ MWh} \cdot 500\frac{\text{g}}{\text{kWh}} \cdot 10^{-6}\frac{\text{t}}{\text{g}} \cdot 10^{3}\frac{\text{kWh}}{\text{MWh}} = 6,692,141 \text{ tCO2}$$

The maximum emission from 13.3 TWh of lignite production is 6.7 million tonnes of CO_2, not even close to what the simulations show. This means that the simulation with electrification includes much more power production than just the extra power demand of Utsira. Alternatively, there may also be mistakes in the code that causes this major difference in emissions. At least one mistake was discovered in the input file of the net transfer capacities between areas, but this can hardly cause such a big change to the emissions.

5.6.1 New simulations to confirm earlier results

With the odd results of electrification leading to an increase of 63 million tonnes of CO2 emissions, a new simulation has been executed to confirm this result. Equal to the last one, this simulation's specifications were:

- Full electrification
- Electrification bug fixed
- "New policies" CO_2 scenario
- Emission costs included

This simulation's results along with earlier results are shown in table (7).

Table 7: Emission results for the 1st and 2nd simulation of "With EL, New policies", as well as 1st simulation result of "Without EL, New policies".

	W EL, "New", 1st	**W EL, "New", 2nd**	**W/O EL, "New"**
Emissions [tCO2]	1 688 043 807	1 602 148 135	1 624 851 906

We see that the 2nd simulation show a total emission that is quite much lower than the first. This means that there have been made mistakes in the simulations, leading to results that were unrealistic.

As the results stand now, electrification will lead to a reduction in emissions. As the gas turbine(s) that are currently used off shore to supply the platforms are not a part of the system model, an increase in power demand can only lead to an increase in emission. This means the simulation "Without EL, New policies" most likely is troubled by the same mistake(s) as the simulation with EL. Another simulation should be done to confirm the results of the "Without EL, New policies".

5.6.2 Last simulation to update earlier results

A second simulation of "New policies, without el" has been done in order to update earlier results, suspecting they are affected by a bug/mistake(s). The results from this simulation were promising, as shown in table (8).

Table 8: Last two simulation's results, showing total system emissions with and without electrification.

	With EL, New	Without EL, New
Emissions [tCO_2]	1 602 148 135	1 593 810 699

We see from table (8) that the CO_2 emissions have gone up by nearly 7.3 million tonnes when electrification is applied.

6 Discussion

In a perfect situation, the results of the model would come out as comparable and not too different from NVE's and Statnett's results, which would indicate that the model works correctly. This requires the model to be bug free and having input parameters that are as accurate as possible, as well as being nearly identical to the other analyses' input parameters. The current results obtained and analyzed for the 2030 and 2060 model does not come from a bug free model. The fuel prices used in the model is also constant, which is a major simplification as fuel prices are expected to change significantly during the next decades[14].

6.1 Power prices

The power prices discussed here is from the results of the last simulation where the electrification bug was fixed, see figure (30).

The most obvious change in power price is the spike around year 2030. The power price increases from 2025, and is decreasing after 2030. Here it would be beneficial to have yearly calculation points to get a more detailed curve. The power demand of Utsira reaches a peak in 2028, which indicates that this is when the impact of the electrification will be largest. It is therefore reasonable to assume that the spike in power prices at this point is a direct result of the high power demand in a1. We also saw a significant decrease in power price after the electrification bug was fixed, which lowered the power demand in a1. This strengthens the assumption that it is the increased power demand that causes the spike in power price. It is however unlikely that the prices will increase as much as show in the figure. The figure represents average yearly power prices, and after comparing with Statnett's and NVE's analyses it seems highly unlikely that prices will more than double from 2025 to 2030.

Prices in a14 rise steadily from around 50 €/MWh to 180 €/MWh from 2020 to 2055. There is not a lot that can explain this huge increase in power price in Germany. If power has to be imported from Germany (a14) to Norway (a1) to overcome the increased demand from Utsira, this may affect the power price, but not under any circumstances by this much. With increasing CO_2 prices in all the simulated scenarios it is found that gas power will have a larger share of the total production in the system. Gas has higher production costs; an increase in gas production may therefore lead to an increase in power prices. However, gas is replacing coal by the single fact that it becomes cheaper when the CO_2 price is increasing, so it should not contribute to higher CO_2 prices.

6.2 Power production

With increasing CO_2 prices it is expected that the most CO_2 intensive industries will decline in the coming years. This is indeed what the simulation to 2055 shows; hard coal production is reduced significantly while gas production sees a slight increase. The result of this is a major decrease in CO_2 emissions. These results are reliable, as they follow what we would expect when the CO_2 price increases. The decrease in coal production is not equal to the increase in gas production, but this is only a result of the extra installed wind capacity.

6.3 Analysis of the "electrification" bug

A "last minute" simulation has been done in order to analyze the impact of the electrification bug. In this simulation, CO_2 prices have also been updated according to the WEO 2016.

For comparison with earlier results, year 2055 has been chosen. According to figure (29), year 2055 is where the impact of the electrification bug should be largest. Production values for both before and after the bug fix is presented in table (9).

Table 9: Production values for all renewable and thermal power production methods, before and after the bug fix.

	Before bugfix [TWh]	**After bugfix [TWh]**	**Difference [TWh]**
Hydro	199.8	192.4	7.421
Lignite	24.19	22.43	1.763
Nuclear	233.3	232.0	1.332
Misc. ren.	49.73	49.32	0.4149
Wind	380.1	379.8	0.3162
Hard coal	18.41	18.12	0.2942
Gas	178.9	178.6	0.2736
Solar	31.92	31.91	0.0038
Oil	0.2399	0.2376	0.0023
Oil & gas	3.447	3.462	-0.015

From figure (29), the difference in load between the two scenarios is approximately 60 TWh. It is obvious from table (9) that the difference between production before and after the bug fix does not equal 60 TWh, but far less. The difference is only 11.8 TWh, which means that nearly 50 TWh is supplied via other sources. It is likely that this energy is transferred into the system by the use of cross border transmission cables.

It is now clear that our 2030 and 2060 model results are not quite as inaccurate as initially feared, as most of the production values are almost identical.

6.4 Quantification of CO_2 emissions

After double checking the 2060 model emission results, the total emissions related to electrification was calculated to be nearly 7.3 million tonnes of CO_2. This is slightly above the theoretical emission limit when we assume that the extra power demand is supplied with the most emission intensive industry, which is lignite coal. One explanation to why the emissions related to electrification exceeds the theoretical limit is that the emission factor of lignite coal in the model may be different from what is used in this thesis.

Factors that can explain why lignite coal is used for this extra production is:

- All other type of production is at maximum production.
- Transmission cables reaching maximum capacity, causing less emission intensive power production to be unavailable (unlikely).
- Fuel prices for lignite coal is too low to be affected by the increasing CO_2 price (likely).

As fuel prices are kept constant in the model, they will be too low when reaching the last iterations. As mentioned, fuel prices are expected to rise, thus making thermal power production less attractive. This is likely the reason why the emissions increase this much when electrification is applied, and should therefore be less if the model uses realistic fuel prices.

Whether the results are completely accurate or not, it is safe to say that the total emissions in the system will increase when Utsira is supplied with power from shore.

6.5 Value of this thesis

For my own learning, this thesis has been very valuable. Problem solving and critical thinking has been a central part of the work, especially when working with the model and its results. Implementing new lines of code to the GAMS model and making MatLab scripts to categorize the results has been challenging and been very helpful with my programming knowledge. Analyzing and understanding the results from the model is both the hardest and most rewarding part of the work, requiring patience and creative thinking.

I believe the contribution of this thesis is substantial for further work. Input parameters have been corrected, bugs have been fixed and discussions have shed light on the development of the work.

The results of the simulations, which include power prices, production data, emissions etc, are of lesser importance. They have shown to be following a generally correct trend based on comparisons with other analyses' results, but several of the graphs show inconsistencies and values that are far off what is reasonable. This concerns mainly the power prices, as well as reservoir level in the system. The general trend in the results is however promising, and with adjustments to the input parameters, like fuel costs and other scenarios of wind and solar capacity, the model should give trustworthy and reasonable results.

7 Conclusion

7.1 Main findings

- Electrification of Utsira will lead to an increase of nearly 7.3 million tonnes of CO_2 in the Nordic power system in the period 2020-2055. The net emission increase is lower than this, as the offshore emissions are not taken into account in this calculation. This number only represents the sum of yearly emissions on a five year basis and does therefore not represent the total emissions in the period 2020-2055. It does however give some idea of the general trend of emissions related to electrification.
- Emissions in 2055 will be near one third of what they are today, mostly as a result of increased installed wind capacity (and thus lower thermal production).
- An increase in installed wind capacity will result in less hydro power production.
- With an increasing CO_2 price as well as increased installed wind capacity, coal production, both lignite and hard coal, will decrease greatly.
- Being less emission intensive than coal production, gas power production will increase as the CO_2 price increases.
- The net import in Norway will increase towards 2030 as the power demand of Utsira increases. No extra power production is started to cover this load, resulting in everything having to be imported.
- Power prices will increase in the southern part of Norway as the power demand of Utsira increases and peaks around 2030. Power prices decrease slightly towards the last years of the simulated years. The model does not take into account the cost of new transmission cables, meaning the modelled power prices will be unaffected by these.

7.2 Further work

To increase the credibility of the results from the model, the input load values should be updated. As the marked analysis by Statnett indicates[13], the power demand will increase significantly towards 2040. In the current state of the model the load is kept constant for all years in the simulation period, thus giving the model potential to simulate more realistic results. Further work should also include:

- Update fuel prices to follow WEO's scenarios. This will increase the accuracy of the model.

- Update the NTC between areas as new cables and transmission lines are being built. Would require a new NTC file for every year of the simulation.
- Simulate variations in installed solar and wind capacity and analyse the differences.
- Change generator input parameters to include new generators as well as remove the ones that are planned to shut down.

List of Figures

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8 References

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