Green or blue hydrogen

Does it matter for the European power market?

THEMA
CONSULTING GROUP

Publication date
07.03.2022

About the project

Project number:	NFR-01-18
Project title:	REMAP
Client:	Norwegian Research Council (NFR)

About the report

Report title:	Green or blue hydrogen – Does it matter for the European power market?
Report number:	2022-04
ISBN-number:	978-82-8368-102-4
Accessibility:	Public

Project description

Hydrogen is considered key to deep emission cuts in the EU. Hydrogen can either be produced from water and renewable power, for the preferred green hydrogen, or from natural gas with carbon capture and storage (CCS) for blue hydrogen. As large amounts of renewable power generation are required to facilitate the energy transition through electrification and general consumption growth, large-scale uptake of green hydrogen puts the power system under even larger pressure. In this model-based scenario analysis, we seek to quantify to what extent blue hydrogen can relieve the pressure, and how the hydrogen types affect the European power system in general, and the value of Norwegian power trade in particular. We find that even with blue hydrogen, the potentials for onshore wind and solar generation needs to be extensively exploited, thus blue hydrogen can ease the strain on renewable resources substantially. On the other hand, less green hydrogen capacity, reduces the flexibility of the system and increases the value of flexible Norwegian hydro generation.

The study is conducted as part of the REMAP research project: https://www.fni.no/projects/remap

Project team

Contact person

Berit Tennbakk
Berit.tennbakk@thema.no
+47 928 68 117

Contributors (alphabetical)

Adrian Mekki
Sigmund Sørensen Kielland

About THEMA Consulting Group

Mail address: Øvre Vollgate 6
Visiting address: Nedre vollgate 9
0158 Oslo, Norway

Organisation number: NO 895 144 932
www.thema.no

THEMA Consulting Group is a Norwegian consulting firm focused on Nordic and European energy issues, and specializing in market analysis, market design and business strategy.

Navigate the energy transition with confidence

CONTENTS

Summary and Conclusions 4

1 Hydrogen is key to deep emission cuts in the EU 7

3 Power market impact – Best Guess scenario 11

4 Power market impact - Emissions Eliminated 15

5 market impacts – Norway 18

6 Conclusions 20

SUMMARY AND CONCLUSIONS

Hydrogen is expected to play a key role in the transition to the low-carbon economy (European Commission, 2020)[1]. Green hydrogen, based on renewable electricity production from wind and solar, seems to be the preferred solution, but may be constrained by the extent to which sufficient renewable electricity volumes can be built out at the required speed. Some therefore see blue hydrogen, based on natural gas with carbon capture and storage, as a bridging technology to accelerate the hydrogen economy in the next couple of decades.

This paper presents a model-based analysis of the power market impact of two scenarios for increased use of hydrogen and illustrates the effects of using blue hydrogen as a bridging strategy. The study looks at how blue hydrogen may reduce the need for new renewables capacity, thus contributing towards alleviating such problems.

Low-carbon hydrogen production key to deep emission cuts

Hydrogen is expected to be a necessary instrument to achieving deep emission reductions, especially in hard-to-electrify segments in the transport and industry sectors.[2]

Currently, most hydrogen is produced in an emission-intensive process based on natural gas (aka grey hydrogen). To reduce emissions while phasing in hydrogen, emissions from hydrogen production must be reduced. The two key low-carbon techniques are *blue hydrogen*, based on natural gas with carbon capture and storage (CCS) technology, and *green hydrogen* from electrolysis based on renewable electricity.

Two scenarios for power markets and two cases for green and blue hydrogen

Green hydrogen is produced by electrolysis, a highly power-intensive process, while natural gas is the key energy input in the production of blue hydrogen. Therefore, the relative share of green and blue hydrogen production is likely to have a significant impact on the European power market. This study quantifies the impacts of different total hydrogen volumes and different shares of blue and green hydrogen on the European power market until 2035.

To investigate the impact of the new hydrogen economy on the European power market, we have developed four study cases. These are based on two scenarios for the development of the European climate policies, power sector developments and hydrogen demand in 2030; in 2035, hydrogen consumption is 200 TWh in the Best Guess scenario and 500 TWh in the Emissions Eliminated scenario. For each scenario, we have analysed the impact of two different hydrogen production mixes, Green Future and Blue Majority. In Green Future we assume that all hydrogen is green, whereas in Blue Majority blue hydrogen covers 75 per cent of the hydrogen consumption.

Green hydrogen scales up an already soaring demand for renewable electricity

Regardless of hydrogen volumes and production technology, the EU needs considerable build-out of renewable electricity capacity towards 2035. Assuming that all hydrogen is to be green (Green Future case), *total renewable* generation capacity is estimated to increase by 665 and 1046 GW in the two scenarios, as renewable capacity is also needed to replace fossil-based capacity in sectors not relying on hydrogen.

Total renewable capacity developments, GW

	Best Guess		***Emissions Eliminated***	
	Green Future	***Blue Majority***	***Green Future***	***Blue Majority***
2020	435	435	435	435
2035	1100	990	1481	1311
Increase	665	555	1046	876
%	153	128	240	200

Source: THEMA Consulting Group

[1] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final, Brussels, 8.7.2020.

[2] Ibid.

The big question is whether such an increase in renewables capacity is possible or will fall short due to problems of public resistance, lack of available areas or delays in grid development.

Blue hydrogen reduces the need for renewable electricity by 16 per cent

Replacing the majority of green hydrogen with blue (Blue Majority case), implies a reduced need for renewable capacity of 110 GW in Best Guess and 170 GW in Emissions Eliminated. The necessary growth in renewable generation is still substantial, but the required growth is reduced by between 25 and 40 percentage points.

German potentials for wind power are fully exploited

To highlight the key findings, we have studied the situation in Germany in greater detail. To provide sufficient renewable electricity to replace fossil and nuclear power production and meet increasing demand from electrification and hydrogen production, *the total assumed potential for wind power generation in Germany is exhausted across all scenarios and cases*.

In the Best Guess scenario, the difference between Green Future and Blue Majority cases is mainly covered by expansion of solar power generation. In Emissions Eliminated, most of the solar potential is exploited in the Blue Majority case and hydrogen imports must increase to cover demand in the Green Future case.

German wind power more worth in Green Future due to fewer zero-price hours

In both scenarios, wind capture prices, i.e., the average prices that wind generation realizes in the market, are higher in Green Future than in Blue Majority. The reason is that more electrolyser capacity enables more hydrogen production periods with in high wind generation and corresponding low prices. Green hydrogen production increases the flexibility to exploit excess wind generation and eases the so-called cannibalization effect, i.e., the negative effect on wind power revenues due to the positive correlation between high wind generation and zero or negative power prices. Increased electrolyser capacity reduces the number of zero price hours.

The higher need for new renewable electricity capacity in the Emissions Eliminated scenario further accentuates the cannibalization effect. The difference in the wind capture price, i.e., the average price wind power producers achieve in the market, between Blue Majority and Green Future cases is also higher in the Emissions Eliminated scenario.

Impacts on the value of Norwegian power exchange

Norwegian annual average power prices do not differ substantially between the scenarios and cases. The capture prices of flexible Norwegian hydro generation are, however, higher in the Blue Majority cases. The reason is that the value of flexibility increases when there is less electrolyser capacity in the system, i.e., the opposite effect as that of less flexible wind power.

The impact on congestion rents differs between the scenarios. Congestion rents depend on hourly price differences. In the Best Guess scenario, the congestion rents are higher in the Blue Majority case than in Green Future due to a higher number of zero-price hours in Europe. This effect is also evident in the Emissions Eliminated scenario, but here even the number of hours with extremely high–price hours is reduced. The combined effect is lower congestion rents in the Blue Majority case than in the Green Future case.

The analysis is simplified, but highlights some core issues

The impact of green vs. blue hydrogen on the European energy system is a difficult field of study, as many crucial market design and regulatory issues are still discussed.

Admittedly, the analysis presented in this memo is highly simplified as we do not model a market equilibrium between blue and green hydrogen or analyse system considerations, such as hydrogen trade, market dynamics and political considerations.

Still, the study demonstrates that regardless of scenario and mix of green and blue hydrogen, Europe will need major additions in renewable electricity capacity to decarbonise its economy, a daunting challenge given current problems in realizing such new capacity and fitting it to the existing electricity system.

The main contributions from the modelling, is the quantification of the additional renewable electricity capacity that is needed to decarbonize the electricity

system, the additional capacity that the demand for hydrogen represents, and the role that blue hydrogen can play. The results show that hydrogen may substantially alleviate the challenges associated with provision of sufficient volumes of renewable electricity capacity to decarbonise the European economy.

The study also shows that the mix of green and blue hydrogen impacts the price structure and flexibility in the power system, thus impacting the value of Norwegian power exchange and flexible Norwegian hydropower.

1 HYDROGEN IS KEY TO DEEP EMISSION CUTS IN THE EU

As the EU has set a target of net-zero emissions, to be reached by 2050 at the latest, all sectors must take up technologies to achieve emission reductions. Hydrogen is seen as a key solution to emission cuts in sectors where direct electrification is difficult to achieve, notably the transport and industry sectors. Thus, the EU needs to develop an industry for low-emission hydrogen production.

The two key modes of producing low-carbon hydrogen are electrolysis based on renewable electricity and reformation of natural gas with carbon capture and storage (CCS), termed *green* and *blue* hydrogen, respectively.

In July 2020, the European Commission (EC) published an ambitious hydrogen strategy.[3] The strategy shows a clear preference for green hydrogen, as this is seen as the only method complying with the EU's long-term climate objectives The EC writes that *"The priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy"*. However, other low-carbon hydrogen production methods, most notably blue hydrogen, are assumed to play a role in a transition period while green hydrogen production and demand are scaled up.

The EC points to expected cost developments as a reason for focusing on green hydrogen. While blue is cheaper than green today, the EC expects no change in the cost of blue hydrogen over the next ten years, whereas the cost of green hydrogen is expected to be more than halved (see Table 1). Thus, the Commission expects green hydrogen to become cheaper than both blue and, in some cases, even grey hydrogen (hydrogen production based on gas without CCS). The key factors explaining the projected cost decline for green hydrogen are reduced costs for both renewable electricity generation and electrolysers.

Table 1 Expected costs for various types of hydrogen in the EC hydrogen strategy

Hydrogen type	***Price today***	***Estimated price 2030***
Grey hydrogen	1.5 €/kg (excluding carbon costs)	1.5 €/kg (excluding carbon costs)
Blue hydrogen	2 €/kg	2-2.5 €/kg
Green hydrogen	2.5-5 €/kg	1.1-2.4 €/kg

Source: European Commission (2020), see footnote 1.

The EU hydrogen strategy proposes a target of 40 GW of electrolyser capacity by 2030. If used at full capacity all year round, this capacity would yield approximately 280 TWh of hydrogen by the use of 370 TWh of renewable electricity, roughly corresponding to the current total generation volume of Norway, Sweden, and Finland combined. The strategy does not set a target for 2050. However, scenarios developed by the EC indicate hydrogen consumption between 1700 TWh and 2500 TWh by 2050. Due to efficiency losses in the electrolysis process, the electricity volume needed to produce the hydrogen would be roughly 30 per cent higher. This shows that despite the uncertainty regarding long-term volumes, the total electricity demand for hydrogen production is likely to be very high.[4]

This point is essential: considerable increases in renewable electricity capacity is required to facilitate green hydrogen production, and to achieve the energy transition in general. Almost half of the electricity generated in the EU today originates from fossil fuels.[5] Replacing this generation capacity with renewable energy would be the first step to cut emissions; installing additional capacity to allow for green hydrogen production would be the second.

As shown below, the volumes of new renewable capacity needed to replace fossil fuel and nuclear generation are already considerable. To cater for the green hydrogen ambitions, massive additional renewable capacity is needed. *The question is, therefore, to what extent is it feasible to aim for dominance of green hydrogen production, and to*

[3] See footnote 1.
[4] EC (2018) – Long-term scenarios See also JRC (2020) – Hydrogen use in EC decarbonisation scenarios.
[5] Eurostat (2019) Gross and net production of electricity

what extent can blue hydrogen relieve the pressure on the power system?

In summary, hydrogen is set to play an important role in the European energy system towards 2050. The way it is produced could significantly impact power and gas markets. Below, we analyse, for a given hydrogen demand, how power market impacts differ between a green hydrogen case, where production is based only on renewable electricity, and a blue hydrogen case, where significant shares are based on natural gas with CCS.

2 MODELLING APPROACH

In the analysis, we use the THEMA power market model with endogenous investments. This implies that the model can invest in new capacity within specified boundaries reflecting realistic potentials for renewable energy in different areas and within different timeframes. The boundaries are developed by THEMA's internal modelling team, and take into account national policy and market frameworks, technology developments, including cost projections, and availability of areas for renewable electricity capacity.

The boundaries for renewables' build-out are highly relevant for this analysis. Whether the full potentials can be exploited in the forecast period is uncertain. Public opposition to investments both in renewable generation, especially onshore wind, and in the power grid, has slowed down investments across the continent. The boundaries applied in our Best Guess scenario reflect this opposition.

Based on cost projections for different technologies, the model chooses to invest in renewable capacity as long as it is economically viable and within the expected potentials. Such endogenous investments are allowed also for electrolysers, while hydrogen demand is set exogenously per country, based on national frameworks, strategies, or more general demand forecasts.

2.1 Two climate policy scenarios and two hydrogen cases

In the model analysis, the two scenarios Best Guess and Emissions Eliminated, based on THEMA's power market projections, are combined with two different assumptions regarding hydrogen production methods, Green Future and Blue Majority, thereby creating four study cases.[6] The drivers for the assessments of the role of hydrogen in the scenarios are the climate policy ambitions, the technology and cost development, economic growth and the power market development (including the value of flexibility).

2.1.1 Best Guess

The *Best Guess* scenario is THEMA's reference scenario for the development of the power market in Europe towards 2050. The scenario sees the fulfilment of the EU's emission reduction targets for 2030 and a decarbonized power sector by 2050.

The market for emission allowances (ETS) is tightened by an increased linear reduction factor, leading to higher carbon prices. Large volumes of renewable electricity capacity are installed, driven partly by support schemes and partly by market forces. Electrification of heating and transport leads to growing electricity demand.

Total hydrogen demand is set exogenously at 197 TWh (corresponding to 260 TWh of electricity demand) in 2035.

2.1.2 Emissions Eliminated

In the *Emissions Eliminated* scenario, we assume that stronger global climate policy commitments ensure that the Paris agreement targets are fulfilled, and that carbon neutrality is achieved beyond the power sector by mid-century.

Unabated coal and gas plants are phased out of the European energy system by 2040 and 2050, respectively. A global carbon pricing scheme is established, increasing the cost of emissions. Renewable energy capacity is built out on market terms and electricity demand soars due to increased electrification as well as hydrogen production. The upper boundaries for renewable build-out are higher than in Best Guess due to stronger political will and public acceptance. Hence, more areas are opened up for renewable build-out, in line with the more ambitious climate policies.

Due to the more ambitious emission reduction policies, hydrogen demand is more than twice as high as in the Best Guess scenario, estimated at 476 TWh (corresponding to 630 TWh of electricity demand) in 2035.[7]

[6] THEMA 2020, Power Market Forecasts

[7] Includes Norway and UK, in addition to EU countries except Bulgaria, Croatia, Greece, Hungary, Romania, Slovakia, and Slovenia.

2.1.3 Green Future and Blue Majority

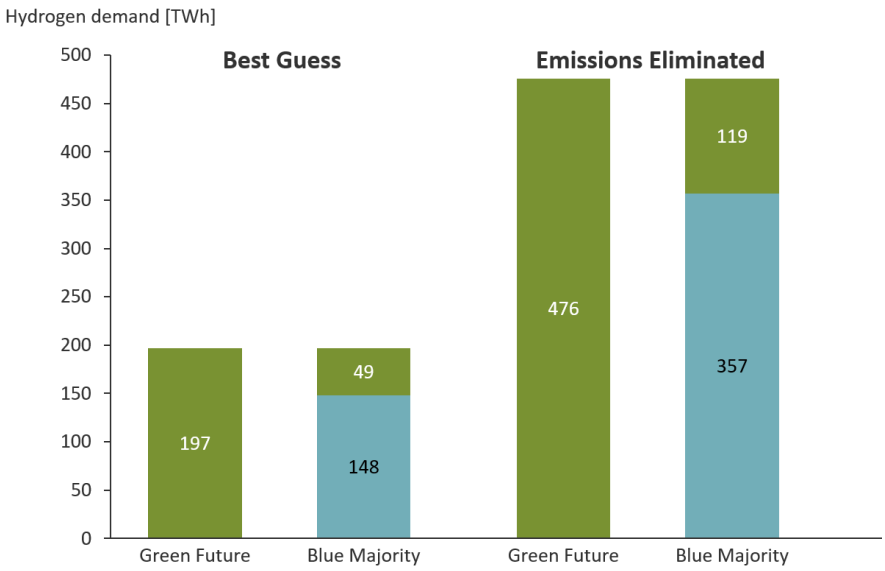
For each of the two scenarios described above, two variations of hydrogen supply are analysed – Green Future and Blue Majority.

In the Green Future case, all hydrogen demand is covered by green hydrogen, i.e., hydrogen produced by electrolysis with electricity from renewable sources.

In contrast, in the Blue Majority case, only 25 per cent of hydrogen supply stems from electrolysis. The remaining 75 per cent is covered by blue hydrogen, i.e., natural gas reforming combined with CCS.

Figure 1 summarizes the four combinations of hydrogen supply in this analysis.

Figure 1 Hydrogen supply from blue and green hydrogen in the two scenarios (2035)



3 POWER MARKET IMPACT – BEST GUESS SCENARIO

In this chapter, we zoom in on the power market impacts of the two hydrogen cases in the Best Guess scenario. The power market impacts of the Emissions Eliminated scenario are presented in chapter 4.

3.1 Europe

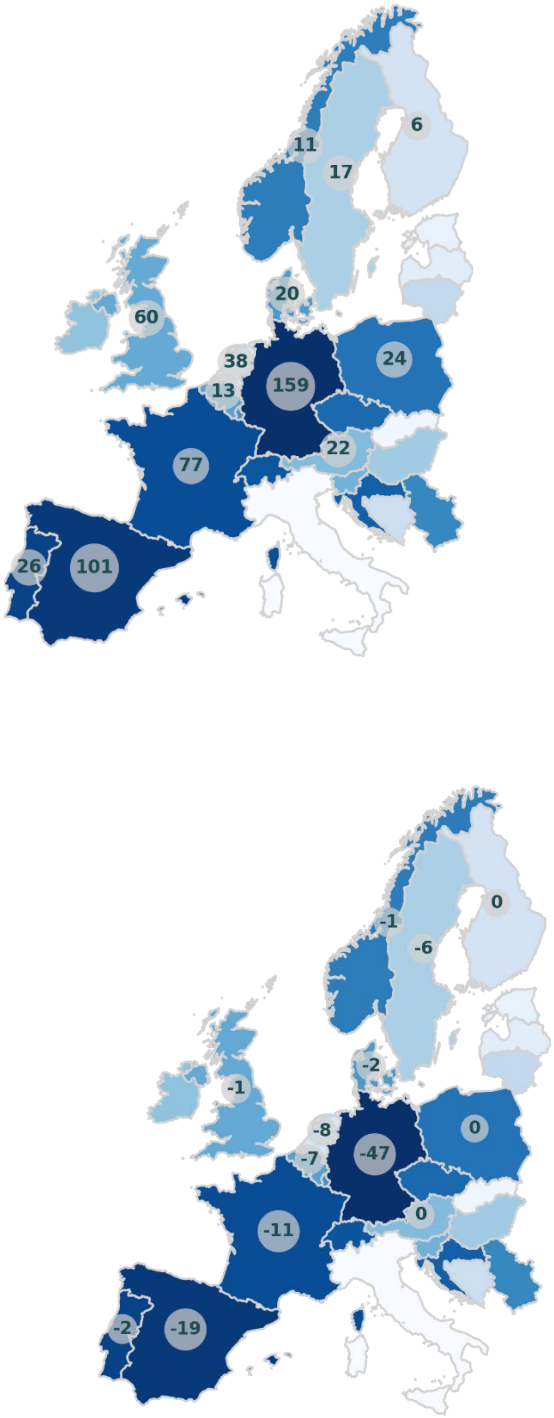
On a European level, increasing demand due to electrification and the replacement of fossil with renewable energy capacity, leads to strong growth in generation capacity.

Figure 2 (top) shows the net increase in power capacity per country from 2020 to 2035 in the Green Future case where all hydrogen demand is covered by green hydrogen. In this case, total generation capacity grows by 66 per cent, from 845 GW in 2020 to 1400 GW in 2035. It should be noted that the growth in renewable capacity is larger than the total *net* increase of 555 GW: Since new investment is also needed to replace the, mostly fossil-powered, capacity that is decommissioned in the period, the renewable generation capacity increases by 655 GW from 2020 to 2035.

Figure 2 (bottom) shows the impact of replacing 75 per cent of the green hydrogen with blue in 2035 (Blue Majority). In this case, the modelling yields 110 GW less renewable generation capacity across the European markets. Compared to the Green Future case, total generation capacity in Europe is reduced by 8 per cent in 2035. Most of the reduction in generation capacity occurs in Germany (-47 GW), Spain (-19 GW), and France (-11 GW), reflecting the high demand for hydrogen in these countries. Other regions, such as the Nordics, are barely affected. But even with green hydrogen constituting only 25 per cent of hydrogen supply, the total net renewable generation capacity in Europe increases more than 50 per cent. This increase is necessary to meet the underlying demand from increasing electrification and the replacement of coal and gas-based capacity.

Figure 2

Top: Changes in generation capacity from 2020-2035 in Best Guess, Green Future
Bottom: Generation capacity in Best Guess, Blue Majority, relative to Green Future [GW]



3.2 Germany

Germany constitutes a pivotal case, as a large market in the centre of Europe with a high amount of hard-to-electrify energy usage and limited renewable energy potentials. Hydrogen production is expected to have a large impact on the power market here. Since the German power market is also directly connected to the Nordic market area, i.e., market developments in Germany are likely to affect the Nordic market, and thus the value of Norwegian power generation as well.

3.2.1 All German wind power potential developed in both cases; 50 GW more solar in Green Future

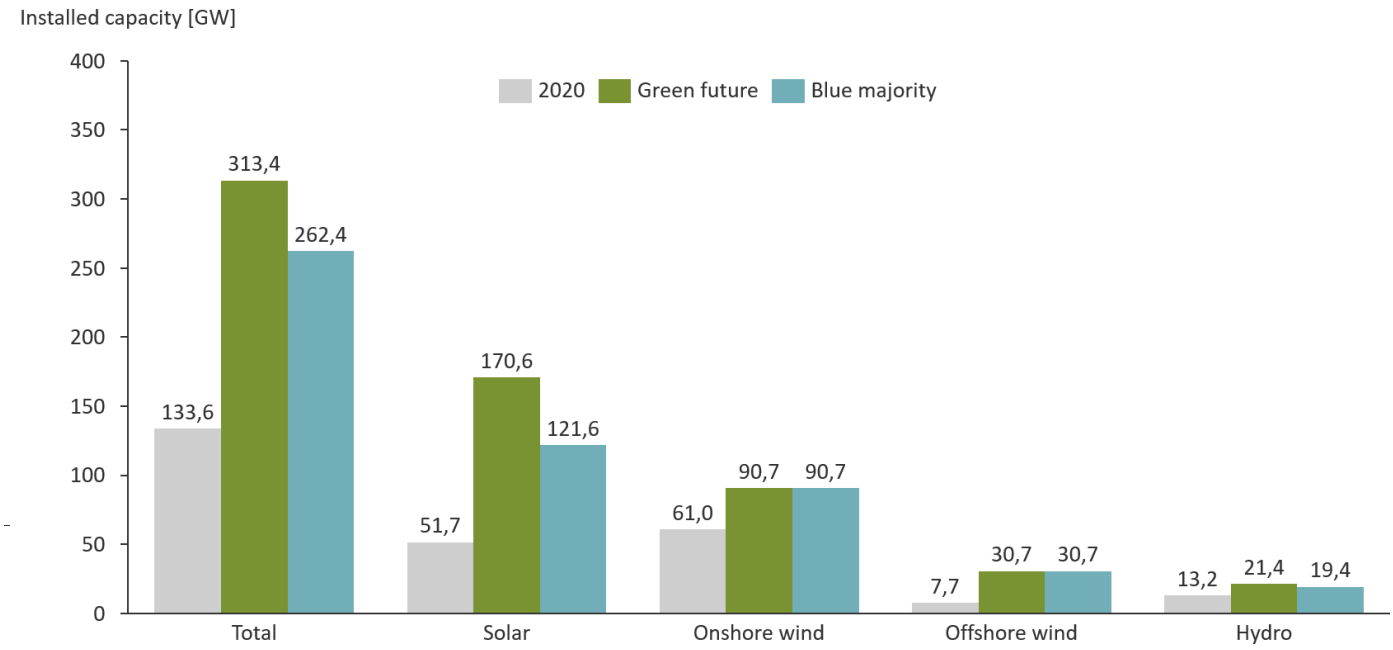
Fossil and nuclear power currently make up almost half of the German power mix. With ambitious political targets for emission reductions, nuclear phase-out, and electrification of end-use sectors such as transport, heating, and industry, the need for new renewable electricity generation in Germany is considerable.

The power demand for green hydrogen production implies an additional need for renewable capacity. As a result of electrification and demand growth, total generation increases from 560 TWh in 2020 to 693 TWh in 2035 in the Green Future case, an increase of 24 per cent. In Blue Majority, the resulting generation is expected to be 35 TWh lower, ending at 658 TWh, corresponding to a total increase in net generation of 17 per cent.

The volumes of domestic renewable energy sources that are economically viable and politically acceptable is however limited. Some of the sources of renewable generation will be fully exploited according to their assumed maximum potentials. Figure 3 shows renewable power generation capacities in Germany in 2020 and, for the Green Future and Blue Majority cases, in 2035. Compared to the 2020 level, the growth in renewable generation capacity is strong in both cases. Even in the Blue Majority case, the renewable capacity must almost double from 2020 to 2035.

The difference between the two cases comes down almost entirely to the solar PV capacity, which is about 50 GW higher in the Green Future case. The reason is that the maximum potential for both onshore and offshore wind power in Germany is already exploited in the Blue Majority case.[8] The increase in power demand in Green Future must therefore be met by an increase in solar power production. As shown in the next section, however, electricity imports are also affected.

Figure 3 Renewable generation capacity in Germany in 2020 and 2035, in Green Future and Blue Majority



[8] The maximum potential used in the modelling is based on investigation of national reports and other knowledge material.

The current generation capacity in Germany is roughly 215 GW. The increase of 159 GW towards 2035, amounts to an increase in capacity by approximately 10 GW every year.[9] As wind and solar are the key technologies contributing to the capacity increase, large areas and technological progress would be needed to ensure such a build-out.

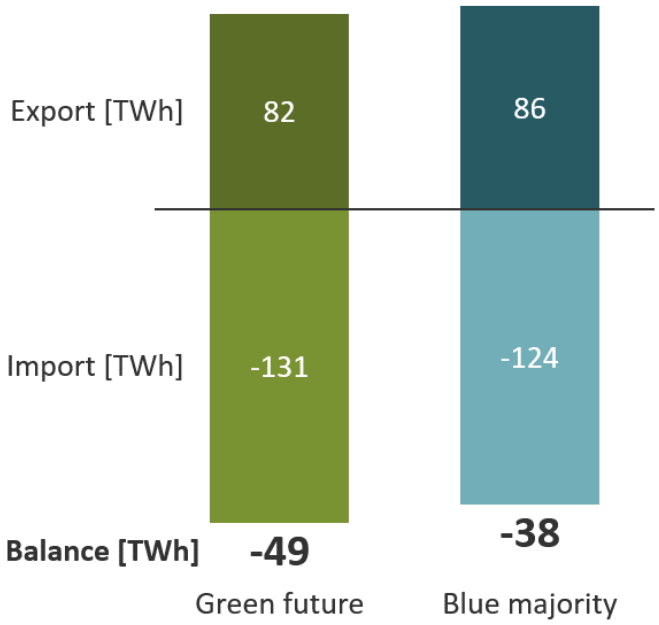
Exploiting the full build-out potential for offshore wind in Germany, as shown in Figure 3, contributes with 30.7 GW offshore wind capacity. For reference, the EU offshore wind strategy aims at 60 GW of offshore wind by 2030.[10] Even if these large RES volumes are technically and economically viable, the efforts and investments required to provide these volumes across Europe are extensive in both scenarios. Our results indicate that the envisioned energy transition will be challenging to achieve as it pushes the boundaries of the RES build-out that is possible to achieve within a 10 to 15-year horizon. Green hydrogen production adds to that challenge.

3.2.2 A high share of blue hydrogen implies lower imports, but a less flexible power system

Despite the substantial increases in generation capacity, Germany still has a net power deficit in the Best Guess scenario in both hydrogen cases, see Figure 4. We make two observations from the results:

- **The need for electricity imports to Germany decreases with blue hydrogen**. Annual net imports in 2035 stand at 49 TWh in Green Future. In Blue Majority, net imports are down by 20 per cent, to 38 TWh. One of the reasons for this is that power demand for green hydrogen production is reduced from 41.8 TWh in Green Future to 10.4 TWh in Blue Majority.
- **High shares of blue hydrogen come with reduced flexibility**. Looking at gross import and export figures in Figure 4, we see that the export volume in Blue Majority is higher than in Green Future. The reason is that larger electrolyser capacity implies that more hydrogen production can be initiated in times of high renewable output, e.g., in hours with strong winds. With lower electrolyser capacity in Blue Majority, prices in high-wind hours are lower and result in increased exports. Thus, the higher electrolyser capacity in Green Future also increases the value of the generation capacity as more surplus wind generation can be stored as hydrogen, as explored further in the next section.

Figure 4 German trade balance in Best Guess for Green Future and Blue Majority



Even though the model results point towards a more flexible power system with green hydrogen, it is uncertain whether this conclusion holds in general. The configuration of the entire generation capacity, the grid configuration and congestion patterns are likely to affect the flexibility of the power system outside of the modelling framework. The results show that electrolysers can provide flexibility, but not

[9] These capacity increases can be compared to the Fosen project in Norway that will be the largest onshore wind project in Europe when finished. The project will raise 277 wind turbines totalling a generation capacity of 1 GW. The envisioned increase in onshore wind capacity in Germany of nearly 30 GW corresponds to the construction of nearly two Fosen-equivalent projects per year.

[10] An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future, COM(2020) 740 final, Brussels, 19.11.2020.

to what extent electrolysers are the preferred solution compared to other types of flexibility.

3.2.3 Low-priced hours are more often used for hydrogen production in Green Future

A closer look at the price structure in the two cases demonstrates the effect described above. Figure 5 shows the duration curve[11] for the German power price for the two cases in the Best Guess scenario. We see that:

- There are 200 more hours with zero power prices in the Blue Majority case. When the power price passes below a certain level, green hydrogen production is economical. Green Future combines more wind generation with more electrolysis capacity. Compared to Blue Majority, the capacity to transform excess wind generation to hydrogen is higher and zero prices are avoided in more hours.
- Although barely visible in Figure 5, Green Future also has a few more hours with high peak prices. The reason is that Green Future has a higher total volume of intermittent renewable capacity and a slightly higher decommissioning of baseload capacity.

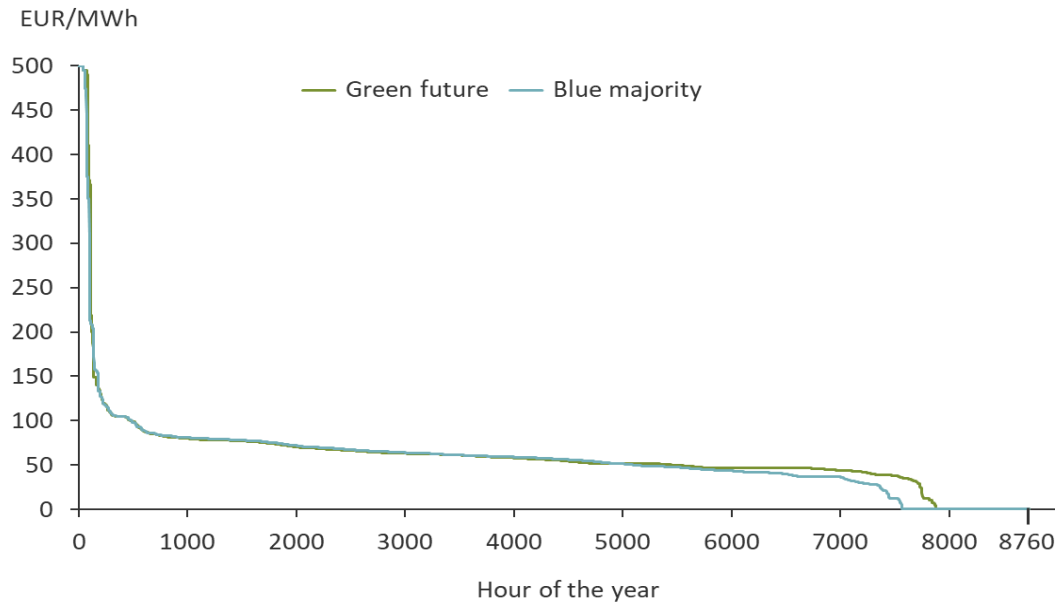
3.2.4 German wind power receives 5 €/MWh less in Blue Majority

The average power prices are found to be 60 €/MWh in Green Future and 57 €/MWh in Blue Majority.

The different duration curves described above also imply a clear difference in the capture prices received by German wind power producers across the two cases, i.e., the average annual power price that wind power receives. While the average capture price amounts to 48 €/MWh in Green Future, it is reduced to 43 €/MWh in Blue Majority.

The difference is primarily explained by the fewer hours with low or zero prices in Green Future. In Green Future, higher volumes of intermittent renewables are somewhat outweighed by the higher capacity to produce green hydrogen, thus reducing the cannibalization effect for wind power. Nevertheless, the capture prices for wind power are lower than the average annual power prices in both cases. In other words, even with the ability to produce more green hydrogen in high-wind hours, there is a notable amount of cannibalization.

Figure 5 Duration curve for German power prices in 2035 in Green Future and Blue Majority



[11] The duration curve shows all 8760 hourly prices during a year sorted from the highest to the lowest price.

4 POWER MARKET IMPACT - EMISSIONS ELIMINATED

4.1 Europe

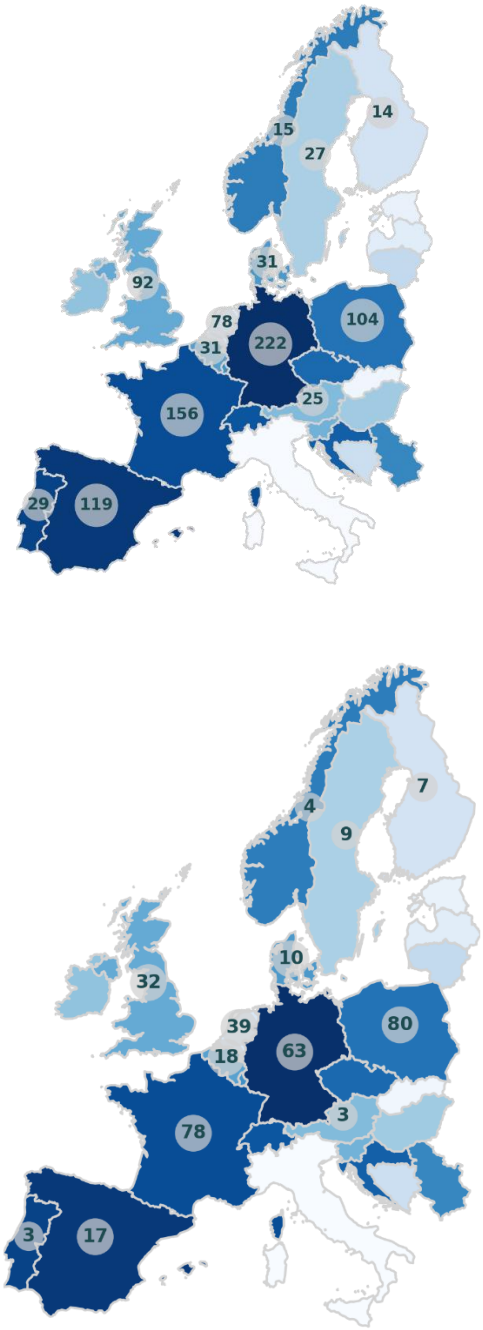
In the Emissions Eliminated scenario, Europe undergoes the green transition much faster than in the Best Guess scenario. This implies that both renewable generation capacity and hydrogen volumes are considerably higher than in the Best Guess scenario in 2035.

Figure 7 (top) shows the resulting net increase in electricity capacity from 2020 to 2035 in the Green Future case. In total, the net capacity increase amounts to 925 GW, yielding a total capacity of 1 770 GW. Compared to the Best Guess scenario, Figure 7 (bottom), total capacity is 370 GW higher. Several countries see capacity growth in the order of hundreds of GW. Most of the additional capacity increase comes in onshore and offshore wind and solar PV, compared to 2020, renewable generation capacity increases by 1046 GW.

Both general electricity demand and hydrogen demand lifts the renewable build-out. If the build-out expected in Best Guess puts the energy system under pressure, that is certainly also the case for Emissions Eliminated. Part of the build-out in Green Future can be compensated by a shift to blue hydrogen. However, as discussed below, most of the renewable build-out is necessary both in Green Future and in Blue Majority.

On a country-by-country level, the impact of switching from Green Future to Blue Majority is smaller in the Emissions Eliminated scenario.

Figure 6
Top: Changes in generation capacity from 2020 to 2035 in Emissions Eliminated, Green Future
Bottom: Generation capacity in Emissions Eliminated, Green Future, relative to Best Guess, Green Future [GW]



4.2 Germany

4.2.1 Renewable capacity increases more than 200 GW regardless of hydrogen type

Figure 7 shows the German renewable energy capacities in Green Future and Blue Majority in 2035, compared to 2020 capacities. As noted above, the maximum potentials assumed for the different technologies are higher in Emissions Eliminated than in the Best Guess scenario. The reason is that this scenario assumes greater public acceptance for renewable generation projects.

Overall, the relative difference between the two hydrogen cases in Emissions Eliminated is smaller than in the Best Guess scenario:

- Onshore and offshore wind power reaches their maximum potentials even in the Blue Majority case, thus there is no difference in the build-out of wind power capacities between the two cases.
- The difference in solar capacity is at a moderate 12 GW. In Best Guess, this difference was 47 GW. The maximum potential for solar power is almost fully exploited in Blue Majority, thus limiting the difference between the cases.

Blue hydrogen reduces the need for large power imports

The power generation used to produce green hydrogen is almost 100 TWh lower in Blue Majority than in Green Future; 31.5 compared to 126 TWh. Power generation in Germany is however only 21 TWh higher in the Green Future case. The higher trade deficit in Germany in the Green Future case is explained by the already high exploitation of the renewable capacity potentials (Figure 7) in Blue Majority. This implies that in Green Majority, net electricity imports increase from 75 TWh to 133 TWh, see Figure 9.

A large part of the 222 GW gross capacity build-out replaces current baseload capacity with intermittent capacity. A higher volume of intermittent renewable generation implies a greater dependency on power trade. This explains why the gross power export from Germany is more than 20 TWh higher in Blue Majority than in Green Future in 2035 (Figure 8). Because the demand for green hydrogen is lower than in Green Future, higher volumes must be exported in hours of high solar and wind power production. Whether German hydrogen is blue or green therefore also affects neighbouring markets.

Figure 7 Renewable generation capacity in Germany in 2035 relative to 2020

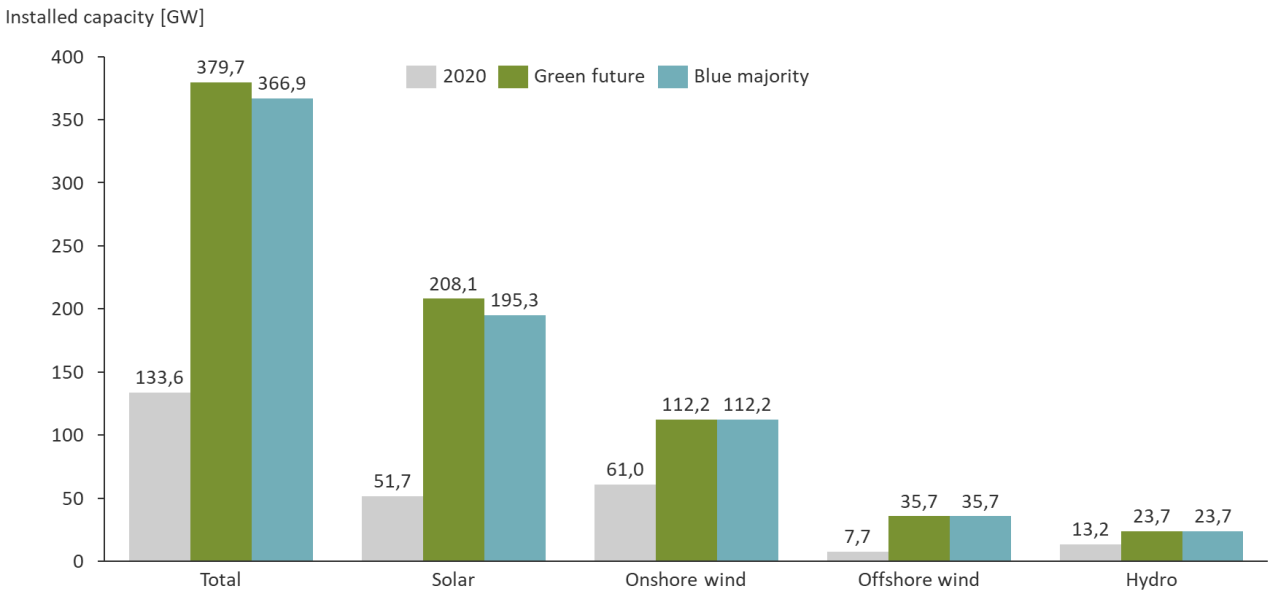
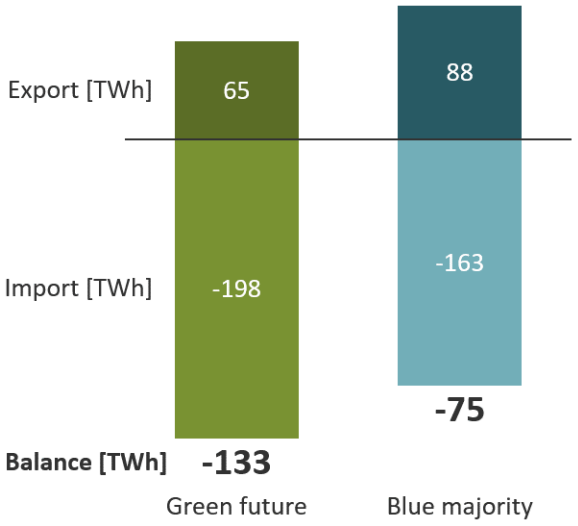


Figure 8 German trade in Emissions Eliminated (2035)



4.2.2 Higher power demand accentuates the difference in power prices between the cases

Figure 9 shows the duration curve for German power prices in 2035 for the two hydrogen cases. The overall trend observed in the Best Guess duration curves (Figure 5) is amplified in the Emissions Eliminated scenario:

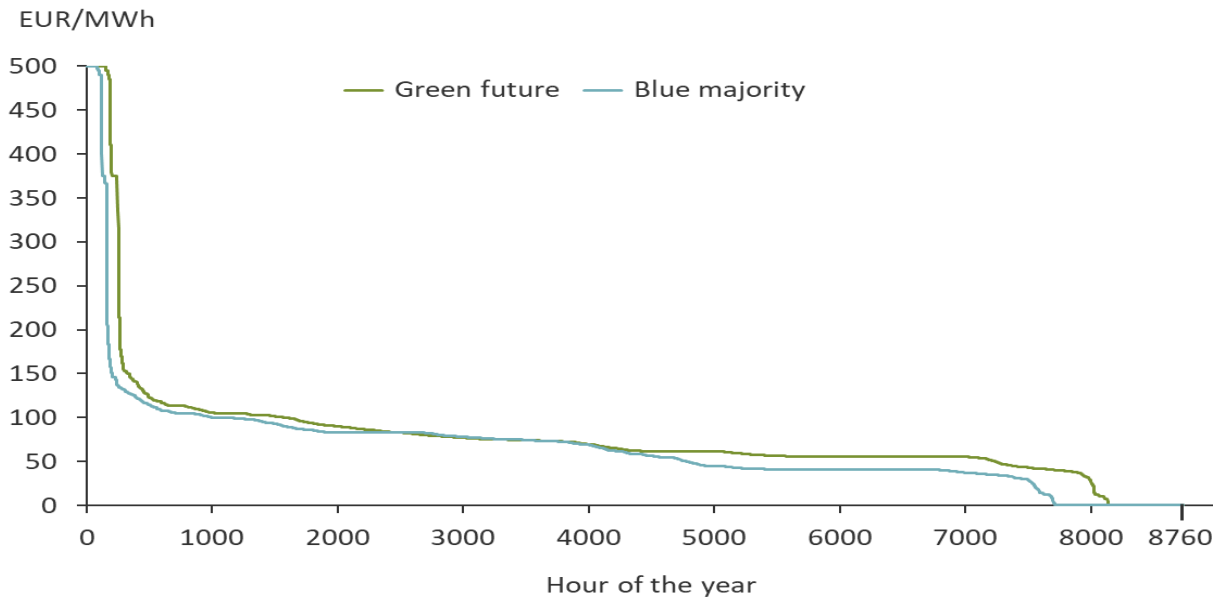
- The number of zero-price hours is lower in Green Future, 600 compared to approximately 1 000 hours in Blue Majority, due to the higher electrolyser capacity in Green Future.
- The corresponding cost of electricity to produce hydrogen is telling: In Blue Majority, the average cost of power as input to green hydrogen production is 12.4 €/MWh lower than in Green Future.
- Green Future also implies more hours with high prices than Blue Majority. The difference between the two hydrogen cases is more prominent than in the Best Guess scenario. This is related to the weaker power balance (increased net imports) in Emissions Eliminated.

4.2.3 The value of German wind power remains lower in the Blue Majority case

The difference in capture prices for wind power in Germany in the two hydrogen cases is also more pronounced in the Emissions Eliminated scenario. While in Green Future, the capture price is estimated at 64 €/MWh, it is 13 €/MWh lower, at 51 €/MWh, in Blue Majority. This underlines the general result, discussed in detail above: The general power market impacts are similar in both scenarios, with accentuated results in the Emissions Eliminated scenario.

The cannibalization effect is mitigated in the Green Majority cases due to higher electrolyser capacity that increases the capacity to produce green hydrogen in hours with low prices and high renewable generation, thus reducing the hours of zero prices and the need for exports. Since wind power can also be used for green hydrogen production, the capture prices are naturally higher in Green Future.

Figure 9: Duration curve of German power prices in the Emissions Eliminated scenario



5 MARKET IMPACTS – NORWAY

The Norwegian power market and the value of Norwegian electricity resources are affected by the production modes of hydrogen, i.e., the shares of green vs. blue hydrogen.

5.1 Power generation

In Green Future, total Norwegian power generation increases to 186 TWh in the Best Guess scenario and 197 TWh in Emissions Eliminated, from around 155 TWh today.

In the Blue Majority cases, however, generation is reduced, by a mere 3 TWh in Best Guess and substantially, by 12 TWh, in Emissions Eliminated.

The differences are mainly attributed to reduced buildout of offshore wind capacity: In Best Guess offshore wind generation is reduced from 13.4 TWh to 10.6 TWh. Corresponding numbers for Emissions Eliminated are 23.3 TWh and 13 TWh.

The reduction is partly explained by lower power demand for production of green hydrogen.

5.2 Trade volumes and congestion rents

Norway has a generation surplus and net export surplus in both scenarios and both cases. And in both scenarios, net exports are higher in Green Future than in Blue Majority.

In the Best Guess scenario, net power exports from Norway are only slightly higher in Green Future than in Blue Majority; 14 and 12 TWh, respectively. However, total trade volumes increase in Blue Majority. This indicates that there is a higher demand for the flexibility offered by hydropower with reservoirs when more hydrogen is blue.

When replacing the majority of green hydrogen with blue in Emissions Eliminated, however, net exports are reduced from 19 to 7.4 TWh, corresponding to the reduction in total generation. While import volumes are largely the same, the reduction in total trade volumes is explained by reduced export flows. Hence, contrary to the Best Guess scenario total trade volumes are reduced when green hydrogen production in Europe is largely replaced by blue hydrogen production.

The trade value, measured by congestion rents, depends on gross trade volumes (imports plus exports) and hourly price differences. Trade values differ between the scenarios corresponding to the impacts on total trade: The total congestion rent on Norwegian interconnectors increases in the Best Guess scenario, it decreases in the Emissions Eliminated scenario.

The largest reduction in the congestion rent in Emissions Eliminated is found towards Germany, where the number of extremely high prices is much lower in Blue Majority. This effect is not seen in Best Guess where the increased number of zero-price hours explains the higher congestion rents.

Table 2: Power prices and hydropower capture rates

	Best Guess		***Emissions Eliminated***	
	Green Future	***Blue Majority***	***Green Future***	***Blue Majority***
Average price DE	59.9	57.2	78.9	66.4
Average price NO	44.5	42	46.8	45.8
Hydro capture price	48.6	46.9	51.8	52.7
Flexibility premium	4.1	4.9	5	6.9

5.3 Annual average prices significantly lower than in Germany

Norwegian average prices are significantly lower than German prices and vary much less from hour to hour. Across the scenarios and cases, average annual prices in Norway *in normal years* vary between 42 and 47 €/MWh. The difference between Norwegian and German average prices is lowest in Best Guess, around 15 €/MWh in both hydrogen cases. In Emissions Eliminated the price difference is largest in Green Future, with the average German price 32.1 €/MWh higher than the Norwegian price. In Blue Majority the price difference is lower but still significant, at 20.6 €/MWh.

5.4 Capture prices for Norwegian hydropower

Capture prices for hydropower generation indicate differences in the value of flexibility. Norwegian hydropower production is highly flexible due to large reservoirs and relatively high installed capacity. This implies that hydropower producers can move production to high-price hours.

The results show that Norwegian hydropower realize an average flexibility premium of 4–7 €/MWh depending on scenario and case and confirm that

the value of flexible and reliable power generation is higher in the Blue Majority cases.

6 CONCLUSIONS

6.1 Green hydrogen scales up an already soaring demand for renewable electricity generation

Regardless of hydrogen volumes and production technology, the EU needs considerable build-out of renewable electricity capacity towards 2035. In the Green Future cases, net generation capacity needs to increase by 555 GW in Best Guess and by 925 GW in Emissions Eliminated between 2020 and 2035.

6.2 Increasing the share of blue hydrogen reduces the pressure to build out renewable generation significantly

By covering 75 per cent of hydrogen demand with blue hydrogen instead of reduces the need for renewable capacity in Europe by between 110 and 170 GW depending on scenario. These volumes represent around 1/6 of the total capacity increase in both scenarios.

The production of blue hydrogen requires input of 18.5 bcm natural gas in Best Guess and 44.5 bcm in the more ambitious Emissions Eliminated scenario. The higher volume corresponds to about 20 per cent of current exports of Norwegian natural gas exports to Europe, roughly 5 per cent of total European gas demand (2020).

6.3 German potentials for wind generation needs to be fully exploited

In Germany, where renewable generation must increase to replace fossil and nuclear power production in addition to cover increasing demand for electrification and hydrogen production, the total expected potential for wind power generation, both on- and offshore, is exhausted even in the Blue Majority cases.

Additional renewable generation needed if all hydrogen is to be green, must be covered by increased solar power generation in Best Guess. In Emissions Eliminated, most of the solar potential is already exploited in the Blue Majority scenario and the higher hydrogen demand is met by increased hydrogen imports.

6.4 Higher capture prices for wind in Germany in Green Future, fewer zero-price hours

Wind capture prices are higher in Green Future than in Blue Majority. The reason is that the electrolyser capacity, that exploits periods with excess renewable generation and correspondingly low prices to produce hydrogen, is higher. This increased flexibility mitigates the cannibalization effect of wind power production. Put differently, higher green hydrogen production implies more flexibility in the power system.

6.5 Norwegian flexibility more worth in the Blue Majority cases

Since there is less flexibility in the system when the bulk of hydrogen demand is covered by blue hydrogen, the value of flexibility increases. This is reflected in the capture prices for Norwegian hydropower which increase by between 0.8 and 1.9 €/MWh higher in the Blue Majority cases.

6.6 The impact on the value of Norwegian power exchange is ambiguous

The value of Norwegian power trade depends on total trade flows, i.e., the sum of exports and imports, and the hourly price differences. When green hydrogen is replaced by blue, the impact on both total trade and congestion rents differs between the scenarios. In Best Guess, total congestion rents increase, while in Emissions Eliminated total congestion rents decrease.

Disclaimer

Unless stated otherwise, the findings, analysis and recommendations in this report are based on publicly available information and commercial reports. Certain statements in this report may be statements of future expectations and other forward-looking statements that are based on THEMA Consulting Group AS (THEMA) its current view, modelling and assumptions and involve known and unknown risks and uncertainties that could cause actual results, performance or events to differ materially from those expressed or implied in such statements. THEMA does not accept any liability for any omission or misstatement arising from public information or information provided by the Client. Every action undertaken on the basis of this report is made at own risk. The Client retains the right to use the information in this report in its operations, in accordance with the terms and conditions set out in terms of engagement or contract related to this report. THEMA assumes no responsibility for any losses suffered by the Client or any third party as a result of this report, or any draft report, distributed, reproduced or otherwise used in violation of the provisions of our involvement with the Client. THEMA expressly disclaims any liability whatsoever to any third party. THEMA makes no representation or warranty (express or implied) to any third party in relation to this report. Any release of this report to the public shall not constitute any permission, waiver or consent from THEMA for any third party to rely on this document.

About THEMA

THEMA Consulting Group is a Norwegian consulting firm focused on Nordic and European energy issues, and specializing in market analysis, market design and business strategy.

THEMA Consulting Group

Øvre Vollgate 6

0158 Oslo, Norway

www.thema.no

Berlin office

Friedrichstrasse 68

10117 Berlin, Germany