Offshore wind development key to meet Sweden's climate and growth targets

for the Swedish Wind Energy Association

The Intergovernmental Panel on Climate Change (IPCC) latest report confirms that it is indisputable that human influence has warmed the climate system, raising global surface temperature. Unless there are rapid, sustained and large-scale reductions of climate change-causing greenhouse gas emissions, the goal of limiting global warming to 1,5 °C compared to pre-industrial levels, as enshrined in the Paris Agreement, will be beyond reach. Sweden has allready set net zero emission target in 2045 and will face a dramatic transformation of their industry and energy sectors to meet this target. In a study project for the the Swedish Wind Energy Association (SWEA), THEMA Consulting looked into the potential consequences for Sweden's power sector, including demand for hydrogen. The scenarios presented in the study were derived in collaboration with SWEA. The scenarios were developed to highlight potential consequences, mechanism, and implications, and should not be mistaken as a prediction.

Key findings include:

- *The electricity demand could grow by between 123 % and 193 % towards 2050 with emission reductions, industry growth and hydrogen production being important drivers.*
- *In order to meet the increased demand, Sweden needs to deploy additional renewable sources, and we find that offshore wind can be a key technology in the transition.*
- *Of the vast technical offshore wind potential that exists in Sweden, we arrive at an expected build-out of 41 GW of offshore wind by 2050.*
- *The Offshore deployments can decrease average prices, price area differences and save grid investments.*
- *We estimate that the build-out and operation of offshore wind could generate up to 165 000 full-time equivalent jobs in Sweden over the period 2025-2050.*
- *The annual employment effect increases over time, reaching up to 10 000 FTEs by 2050.*
- *Offshore wind wind will contribute with SEK 20 bn in tax income.*

Background

On behalf of SWEA, THEMA Consulting evaluated potential future scenarios for the Swedish power sector, including demand developments for hydrogen. The scenarios presented in this report and evaluated in the study were derived in close collaboration with SWEA.

We find that the current energy transition with ambitious climate targets will lead to a dramatic transformation of the power sector, with strongly increasing demand, also in form of hydrogen generation and sector coupling. Sweden's offshore wind resources can play an important part in this transition, and in order to highlight the role we developed different scenarios[1] to understand consequences, mechanisms, and implications:

- Offshore Wind scenario: In this scenario we allow investments in offshore wind, within limits of the technical resource potential that was estimated to be in magnitude of 161 GW.
- Base scenario: A base scenario in which we do not allow for offshore investments. This serves as a benchmark and point of comparison for the offshore scenario, and highlights some of the associated challenges, as for example grid bottlenecks.

We model the two scenarios for 2030 and 2050 to show the development over time and shed light on how Sweden can achieve their own climate and energy targets and play a role in the EU energy transition, as EUs long term scenarios show a need for significant volumes of offshore wind in the Baltic Sea.

The electricity demand could grow by between 123 % and 193 % to 2050

In a fully electrified Sweden we see that electricity demand could increase from the current level of 141 TWh to between 315 TWh and 413 TWh by 2050, where 371 TWh is used in our offshore Wind and Base scenarios. The demand growth has three main causes:

1. Energy-related processes must transition to net zero emissions by 2045, in line with adopted climate policies.
2. The industry sector is expected to keep growing in the long term, particularly new forms of power-intensive industry.
3. As demand for green hydrogen will increase, driven by decarbonising energy-related processes and establishing green hydrogen as a new form of industry, significant amounts of electricity will be needed for production.

Demand developments are highly uncertain in the long term. In the last year a number of projects have been announced that, if realised, alone would increase electricity demand with tens of TWh to 2050. Depending on how the energy system develops, and the policies put in place we believe that an electricity demand anywhere between 315 to 413 TWh is consistent with full electrification and net zero emissions. Consumption will tend towards the higher end of the interval if a greater share of fossil energy use can be electrified directly, or if future power-intensive industry growth exceeds our main assumptions. In the lower end, the potential for electrification turns out to be lower than assumed, while less industry growth is realised domestically. Figure 1 shows demand developments in our main scenario together with upper and lower bounds on what can likely remain consistent with emission reduction goals and extensive electrification.

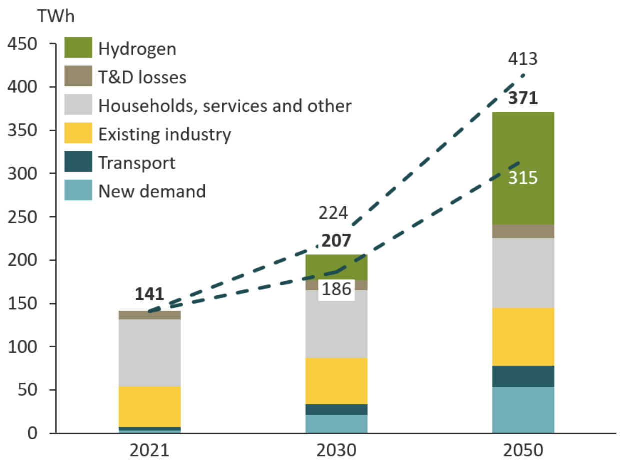


Figure 1: *National electricity demand by sector. Dotted lines represent uncertainties..*

Across existing sectors electricity demand increases as energy-related processes are electrified. In the transport sector, electricity use increases by a little over 20 TWh, primarily driven

[1] The scenarios are not to be mistaken as predictions or forecasts, but are meant to inform about mechanisms, consequences, implications, and magnitudes. Needless to say that one could also use alternative assumptions to derive at alternative outcomes. Factors including public acceptance, permitting processes, grid availability and support schemes will affect the outcome. Nevertheless, some of the results, such as demand increase and the potential offshore volumes that can be deployed to meet the increasing demand, are robust.

by the gradual replacement of passenger cars and other road traffic with Electric Vehicles (EVs). The industry sector increases its electricity demand by nearly 20 TWh to 66 TWh, with notable contributors being the cement and chemicals industries. Iron and steel manufacturing becomes major drivers of electricity consumption by becoming large consumers of green hydrogen, but this electricity use is counted in the *Hydrogen* category rather than *Existing industry*. Demand from households, services and other sectors is expected to remain relatively flat around 80 TWh, as population and economic growth is largely offset by energy efficiency measures.

A growing industry sector adds around 50 TWh of new demand towards 2050. Nearly 30 TWh of this growth is expected to come from projects in fossil-free steel manufacturing, like HYBRIT, LKAB and H2 Green Steel (H2GS), data centres and battery factories, such as Northvolt Ett in Skellefteå. The final 20 TWh of growth is assumed to come online in the longer term as unspecified power-intensive industry, which could be more of the categories listed above or new emerging sectors.

Production of green hydrogen through electrolysis increases electricity demand by 130 TWh if coupled with significant build-out of wind power. Sweden is likely to demand large amounts of green hydrogen in the long term, particularly in the industry sector in northern Sweden. Assuming that electrolysis is market-driven we find that local production of green hydrogen likely will exceed local demand in the long term, making Sweden a net exporter. Our hydrogen demand assumptions are estimates of the total demand, with the main focus being on hydrogen use in the industry sector. Hydrogen demand in other sectors, such as international air and sea traffic, is more uncertain, and could potentially grow larger than we assume.

The offshore wind potential is significant

Against the increasing demand, new renewable resources need to be deployed. Alongside onshore wind and solar PV, offshore wind is a promising candidate to cater the increase. As part of the study, we therefor also estimated the resource potential for offshore wind in Sweden, taking constraints for available areas into account.

To arrive at the technical offshore wind potential we assume that any area assigned primarily to a marine activity other than energy (*energiutvinning*) is excluded for offshore wind deployment. We include areas that fall under the category of general use as these may qualify for offshore wind installation in the future. Figure 2 shows the spatial exclusions (left) and the resulting available area for offshore wind deployment (right). Any shaded area on the left figure is excluded from the available area (blue) in the right graph. In addition, Figure 2b compares the available area identified in this study to the areas assigned to *energiutvinning* in the Swedish Marine Spatial plan.

We estimate the total available area for offshore wind development to around half of the total seabed area of Swedish waters of 165 000 km^2. Spatial constraints limit the available area for offshore wind deployment to 84 900 km^2. Within this area, 80 300 km^2 experience average wind speeds greater than 8 m/s at 100 m. Using the assumed capacity density of 2 MW/km^2, we thus estimate the technical potential for offshore wind in Swedish waters to 161 GW.

Figure 3 provides a comparison with other studies that estimate the technical potential of offshore wind in Sweden. The potential estimated in this study lies above the estimates for technical potential, and those technical potential studies that only account for bottom-fixed foundations. The fact that this work accounts for national plans of marine space utilisation results in a lower technical potential than the most optimistic studies with few spatial constraints.

Build out of 41 GW offshore wind is economically viable

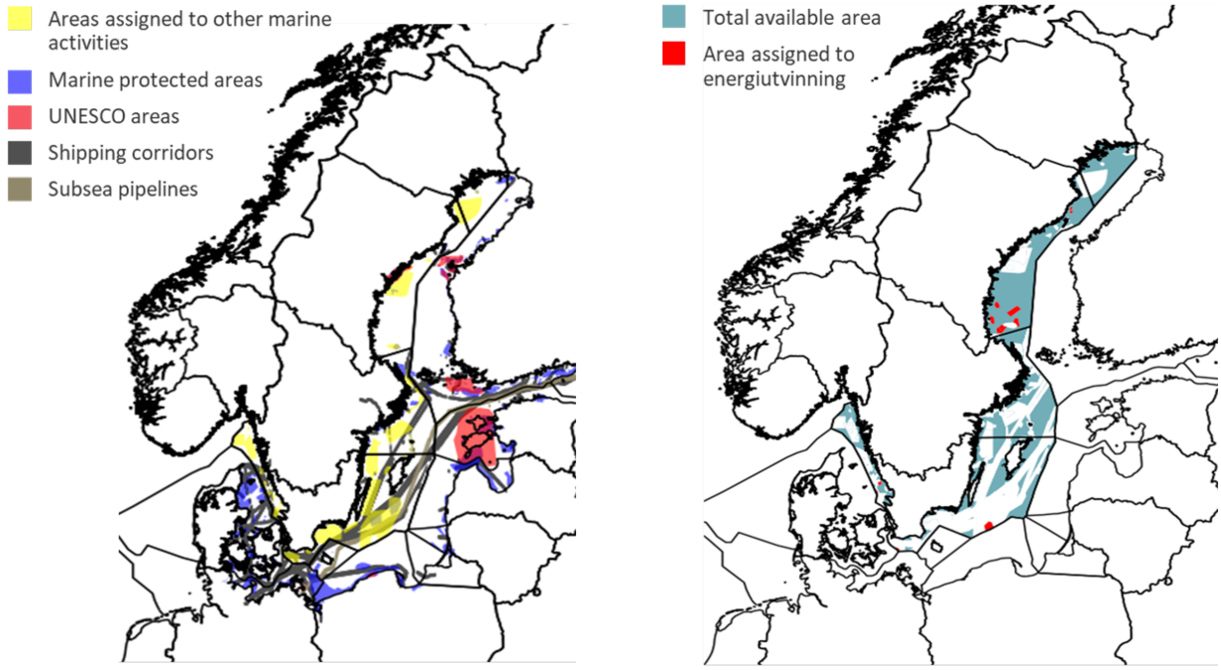
The increase in demand, alongside the shift towards a renewable power system will require a large addition of capacity from Renewable Energy Sources (RES). However, the pathway towards such a system can differ signifcantly.

Based on the assumptions for demand development and the estimated technical potential for offshore wind we analyse two future scenarios. Firstly, the *Offshore Wind scenario* allows for market-driven investments in all technologies up to their technical potential. As a comparison, the *Base scenario* illustrates a power system without offshore wind, where solar PV and onshore wind play a larger role. In addition, a sensitivity where 10 % of the offshore wind capacity by 2050 is allocated to offshore hybrid assets (*Offshore Hubs scenario*) is analysed[2].

In the scenario where we allow for offshore investments (*Offshore Wind scenario*), we see that large volumes of offshore wind are built out cost efficiently. Of the vast technical potential, we see that 41 GW of offshore wind are economically viable, i.e. can be built out cost efficiently by 2050, which equals approximately 25 % of the technical potential for offshore wind. We see that offshore wind primarily is built in SE3 and SE4, the two southernmost price zones in Sweden.

The resulting capacity mix in Sweden for the *Offshore Wind scenario* and the *Base scenario* is shown in Figure 4 for the years 2030 and 2050. Towards 2030, a total of 41 GW of capacity stems from new RES of which the largest share comes from onshore wind (27 GW) and solar PV (12 GW). Compared to these technologies, the build-out of offshore wind is moderate in 2030, as the Levelised Cost of Electricity (LCoE) of offshore wind is still higher than that of solar PV and onshore wind in locations with favourable resource conditions. Beyond cost considerations, the investment in RES technologies also depend on factors such as permitting processes, grid availability, support

[2] Hybrid asset refers to the combination of transmission and generation capacity



(a) *spatial exclusions.* (b) *available area.*

Figure 2: *Spatial considerations*

schemes and public acceptance. A more favourable development than today, may lead to a more rapid build-out of offshore wind than illustrated in the *Offshore Wind scenario*. Investments in offshore wind increases significantly after 2030. Towards 2050, as available onshore sites become exploited,the cost of offshore wind decreases and electricity demand has increased due to electrification, large capacity additions from offshore wind are expected in this scenario. In total the RES build-out towards 2050 amounts to 41 GW of offshore wind capacity, 33 GW of solar PV and 32 GW of onshore wind. These technologies account for 77 % of generation in 2050, compared to 42 % in 2030.

In the alternative scenario (*Base scenario*) we show the impact of a power system without offshore wind in Sweden. The volumes of offshore wind generation from the *Offshore Wind Scenario* are substituted by generation from onshore wind and solar PV, within restrictions of potential and economic viability. The *Base scenario* has higher installed capacity than the *Offshore Wind scenario* in 2050 due to lower Full-Load Hours (FLH) from the technologies that are needed to replace offshore wind. In total the *Base scenario* has 133 GW of capacity from RES other than hydro and bio energy. Onshore wind capacity (70 GW) and solar PV capacity (63 GW) are approximately twice as high as in *Offshore Wind scenario*. Despite higher installed capacity, the generation output from the *Base* scenario is approximately 30 TWh lower than in the *Offshore Wind scenario* in 2050, as shown in Figure 5. This implies a change in supply/demand balance for Sweden. Also, due to internal bottlenecks in Sweden, some generation from onshore wind in the northern zones is also curtailed (voluntary curtailment at zero prices).

In none of the scenarios we see nuclear power in 2050 as it is not profitable to complete necessary investments to prolong existing reactors lifetime nor do we see investments in new nuclear capacity being profitable.

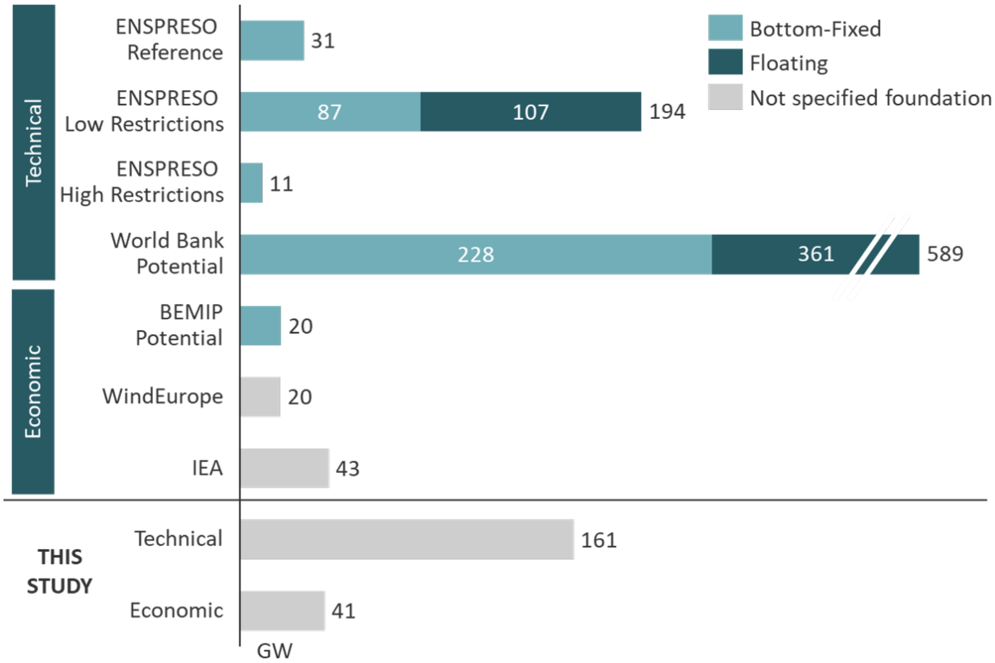


Figure 3: *Comparison of existing potential studies for offshore wind in Sweden.*

Sweden stays net exporter and adds hydrogen to trade portfolio

Electricity trade

At present Sweden is a net exporter of electricity with sufficient generation to cover national power demand and exports to neighbouring countries. As the power system changes dramatically towards 2050 with increased demand, new technologies and more volatile generation patterns, trade between regions will also be affected. Figure 7 shows the trade balance for Sweden in 2030 and 2050 for the *Offshore Wind scenario*, the *Base scenario* and the *Offshore Hubs scenario*.[3]. For each country exports are shown on the negative axis while imports are shown on the positive axis. The sum of imports and exports as well as the balance (bold) are provided next to the bars.

In 2030, Sweden is a net exporter in all scenarios with a balance of 21 TWh. By 2050, the large increase in domestic power demand requires additional capacity to maintain Sweden's role as a net exporter. In the *Offshore Wind scenario* exports are marginally decreased compared to 2030 while imports increase significantly, mostly from Norway and Finland, leading to net exports of 4 TWh. In the *Base scenario* Sweden becomes a net importer with a balance of 10 TWh imports.

[3]The Offshore Hubs scenarios is identical to the Offshore Wind scenario in 2030

Hydrogen trade

The supply-demand balance would also affect hydrogen volumes produced in Sweden. The coupling of power and hydrogen sector was also taken into account in our analysis. Figure 8 shows the supply of hydrogen for the *Offshore Wind scenario* and the *Base scenario*. In both cases, most of hydrogen demand is covered by domestic production of green hydrogen through electrolysis. In Sweden, hydrogen demand mainly stems from the industry and transport sectors and no or little hydrogen demand for power generation (G2P) is expected. For the *Offshore Wind scenario* the production of hydrogen in Sweden exceeds national demand resulting in exports to neighbouring countries. In the *Base*

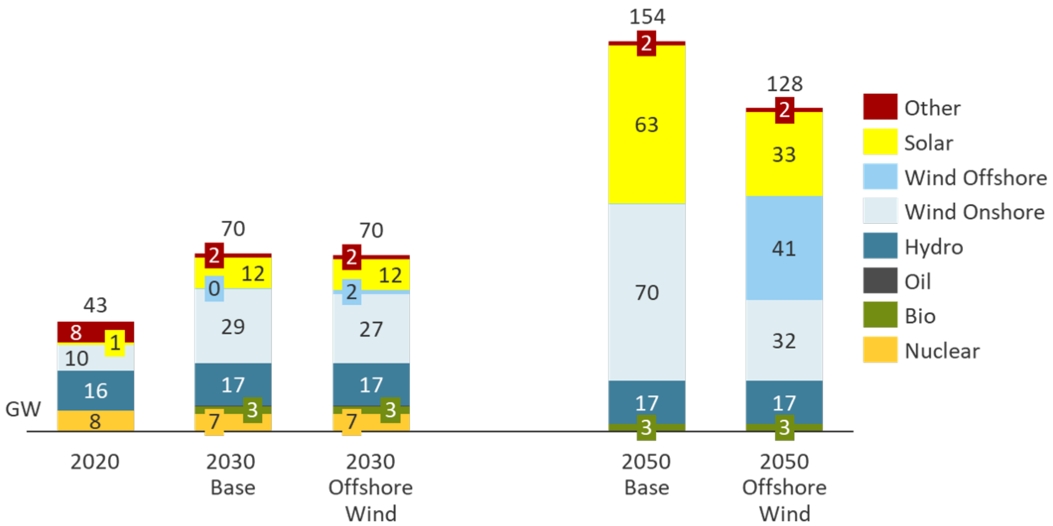


Figure 4: *Capacity mix in Sweden for the Offshore Wind and Base scenarios*

scenario, some imports of hydrogen from outside Sweden would be needed to cover hydrogen demand[4].

Note that figure 8 shows hydrogen demand and supply in TWh hydrogen, to derive the power demand to produce these volumes of green hydrogen the conversion efficiency which typically lies between 60 to 80 % has been accounted for.

Offshore deployments can decrease price area differences

In the *Offshore Wind scenario*, offshore wind resources are well aligned with the demand centres in the South, and price differentials across Sweden are much lower than inthe *Base scenario*. As described, the *Base scenario* leads to large onshore deployments in the north. This, in turn, aggravates the internal bottlenecks in Sweden. Without significant additional grid upgrades, reflected by high price differential between northern and southern Sweden in this scenario.

[4]Note that figure 8 shows hydrogen demand and supply in TWh hydrogen, to derive the power demand to produce these volumes of green hydrogen the conversion efficiency which typically lies between 60 to 80 % has been accounted for.

Figure 6 shows a comparison of average power prices for the *Offshore Wind scenario* and the *Base* scenario. The dashed line illustrates the average price for Sweden, while each line corresponds to the price in one zone. For the *Offshore Wind scenario* the Swedish power price decreases from a level of 46 EUR/MWh in 2030 to 42 EUR/MWh in 2050. In 2030 small regional differences in price between north and south are visible with a spread of 2 to 3 EUR/MWh between SE4 and SE1. Towards 2050 power prices in all zones decrease and the large build-out of offshore wind in the south leads to SE4 experiencing the largest reduction in power prices.

In the *Base scenario* regional differences are much more pronounced. The zones in the north experience a large build-out of onshore wind, which coupled with grid bottlenecks leads to decreasing prices, especially in SE1. The southern zones, where most demand centres are located, will have a large imbalance between supply and demand. In 2050, the spread between power prices in SE1 and SE4 is close to 18 EUR/MWh. Overall, Swedish power prices are expected to increase from 46 EUR/MWh in 2030 to 48 EUR/MWh in the *Base* scenario.

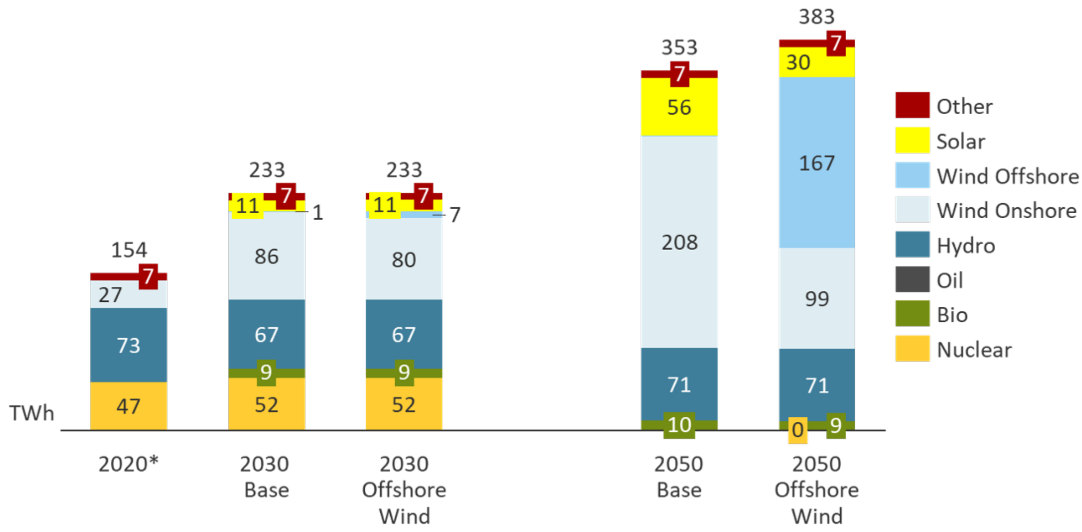


Figure 5: *Generation mix in Sweden for the Offshore Wind and Base scenarios*

Offshore wind deployment can save billion 142 SEK in grid investments

The analysis show that by allowing for offshore wind investments, we will have a smaller imbalance between supply and demand in southern Sweden, leading to less need for grid upgrades.

A scenario with so high price differentials as in the *Base scenario* may be challenging for market participants, policy makers, and grid operators. It will particularly have negative effects on customers in the South of Sweden and producers in the north. Hence, it is likely that such an onshore scenario would need to be accompanied by grid investments. We therefore investigated what grid investments may be necessary in such a scenario, using a grid model and grid data for the Nordic market. The costs for such grid investments can be interpreted for saved grid investments in the case of offshore deployment with a better match against demand.

Figure 9 shows the bottlenecks identified in the *Base Scenario* before any grid upgrades. The red lines indicate that there is some congestion within the Nordic area. Given that physical flows do not travel strictly from north to south, critical bottlenecks occur not only within Sweden, but also outside Sweden and between countries.

We considered both High Voltage Direct Current (HVDC) upgrades (for long-distance upgrades) and AC upgrades for shorted distances. We then re-ran the grid and dispatch model to see whether the grid upgrades reduced the overall congestions, reflected in price differentials, line utilisation, and identification of critical lines.

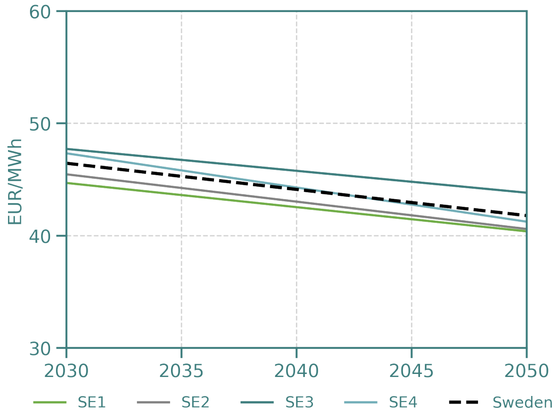
Using this approach, we estimated both grid investments in the *Base Scenario* and the *Offshore wind Scenario*. The difference in implied grid investments is in magnitude of billion 142 SEK[5], with the *Base Scenario* implying the higher costs. Thus, this estimate can be interpreted as saved grid investments in the *Offshore wind scenario* compared to the *Base Scenario*.

The bulk of the total costs is comprised of the HVDC upgrades, while the AC upgrades represent a little under 10 % of the total costs.[6].

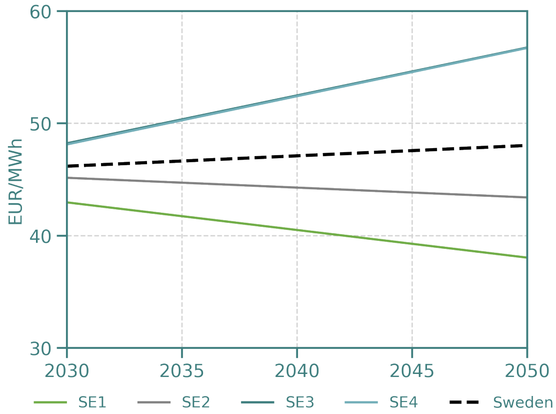
[*] 2020 values from ENTSO-E not corrected for weather

[5] In the cost estimate figures, we include cable/line costs, transformer/converter station costs (depending on technology) and installation costs

[6] Our numbers are a rough estimation with a large margin of error, as the specific technological requirements will depend on geographical conditions and other factors whose effect we do not fully capture in this study



(a) *Offshore Wind scenario.*



(b) *Base scenario.*

Figure 6: *Power prices by zone for the Offshore Wind and Base scenario*

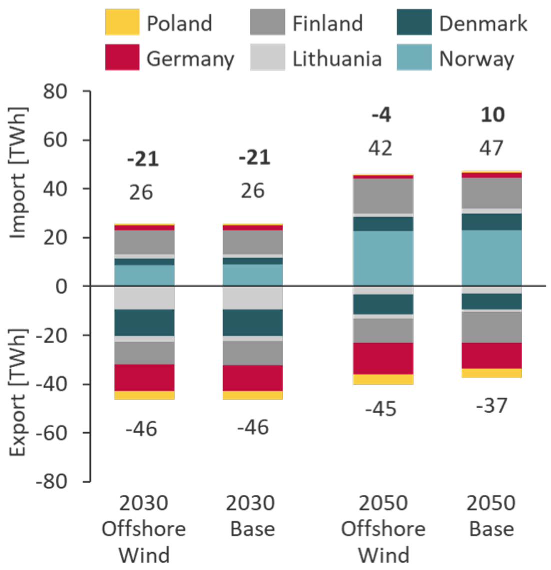


Figure 7: *Trade balance by country for the Offshore Wind and Base scenario*

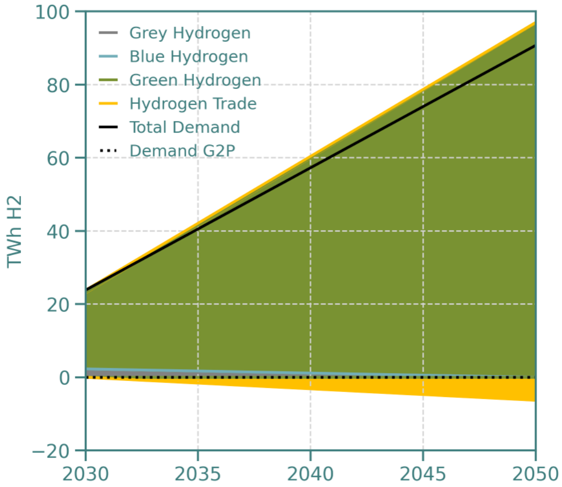
Offshore wind would not require additional grid reserves

Also related to grid issues, we investigated the need to backup capacities in the different scenarios. Assuming that the system operator prepares for the worst-case scenarios, we estimate that the reserve needs in the scenario with offshore wind and the scenario without offshore wind, but with additional grid upgrades are largely equal. We have based this conclusion on the simulation of different weather years, and estimating the maximum supply-demand gap that would need to be covered by backup capacities, demand response, or other means. What differs somewhat between the two scenarios is the location of required backup capacities, but not the total volume (see Figure 10).

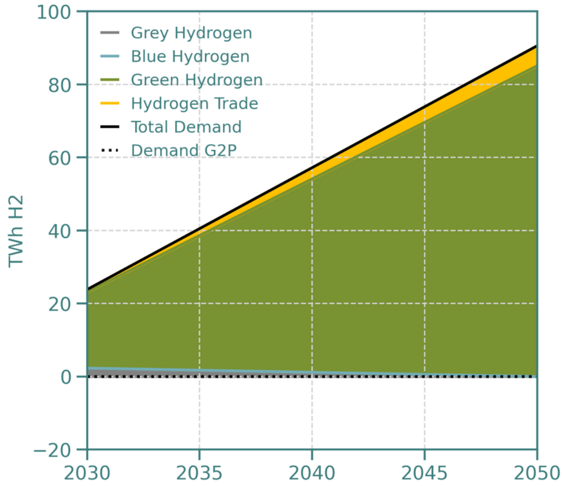
Investing in Hybrid Offshore Assets is beneficial

A much discussed topic is the utilisation of offshore wind in form of hybrid assets. We have also run a sensitivity where we look at the impacts of investing in so called hybrid offshore assets. We implemented a scenario where 4 GW of offshore wind in Sweden is assigned to hybrid assets. Each hub of 2 GW capacity has 1,5 GW capacity transmission capacity to SE4 1,5 GW export capacity to Germany and Poland respectively.

Figure 11 shows the average power prices for all zones including the offshore hubs in 2050. The hubs see prices that are slightly lower than in the connected onshore zone with the lower power price and above the capture price of the offshore wind assets. When compared to the results for the *Offshore Wind scenario* without hybrid assets a stronger coupling between power prices in south-



(a) *Offshore Wind scenario.*



(b) *Base scenario.*

Figure 8: *Hydrogen by source for the Offshore Wind and Base scenario*

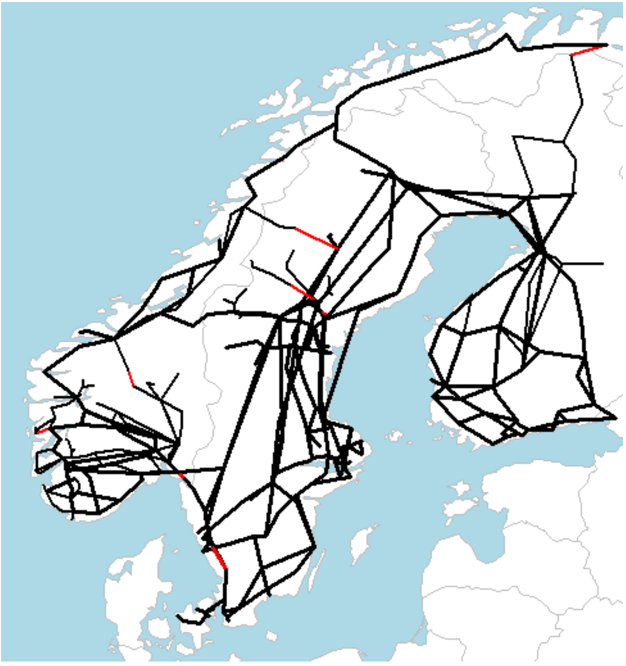


Figure 9: *Critical congestions (in red) identified in the Base Scenario in 2050 before any grid upgrades.*

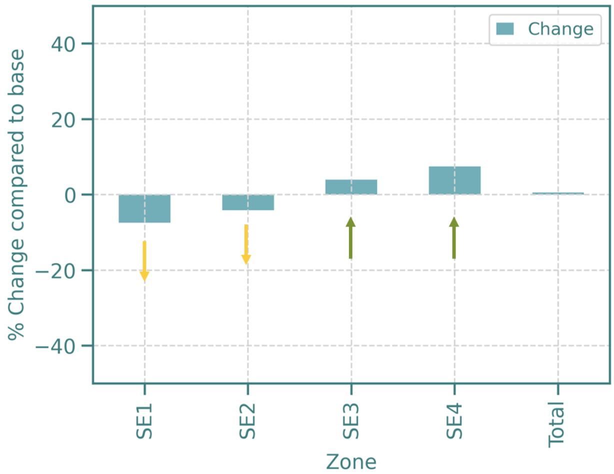
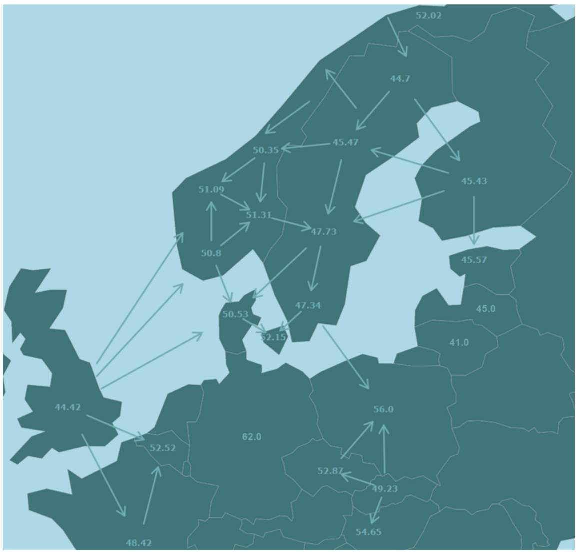


Figure 10: *Illustration: capacity requirements might change between bidding zones (the location of the supply gap is different).But total reserve requirements are similar between the offshore wind scenario and a very highly interconnected Swedish grid*

ern Sweden and central Europe can be observed. Power prices in SE4 increase by approximately 3 EUR/MWh while power prices in Germany and Poland decrease by 2 EUR/MWh.

Thus, the additional trade capacities typically lead to a stronger price convergence, benefiting consumers in deficit areas and producers in surplus areas. Additional benefits are reflected by the congestion rent on lines to and from the hubs [7]. Furthermore, combining generation assets with

[7] congestion rent on hybrid assets would need to be weighted against changes in congestion rent on other interconnectors



(a) *Offshore Wind scenario 2050.*

(b) *Offshore Hubs scenario 2050.*

Figure 11: *Map of zonal average power prices*

interconnector assets also has an impact beyond what is measured by consumer surplus, producer surplus, and congestion rent, namely increased market integration (and effect on e.g. competition, liquidity) and effects on security of supply. Increased integration will further lead to better utilisation of Europe's renewable resources lowering the cost of the energy transition.

Build-out of offshore wind will lead to significant effects on employment and value added

The build-out and operation of offshore wind power lead to employment effects in Sweden of 50 000 - 165 000 full time employees FTEs and value added in the Swedish supply chains of SEK 60 - 200 billion for the period 2025-2050 for the low and high case respectively.

The employment effect in Sweden is expected to increase over time. By 2030, it is estimated to reach 1 100 - 4 000 FTEs before rising gradually reaching up to 10 000 annually by 2050 of which almost half are related to the operation of the offshore wind assets.

The significant range in results stems from the uncertainty related to the share of the total goods and services demanded from the offshore wind power projects that is delivered from companies in Sweden. It is hard to determine how this share might develop towards 2050. However, a strategic focus on developing competitive, domestic industrial segments, both from the government and industry, is likely to contribute to capturing a larger share of the total market.

Offshore wind wind will contribute with SEK 20 bn in tax income

The offshore wind power projects will in addition contribute with considerable tax income over their operating lifetime. The corporate tax from offshore wind is estimated at SEK 20 bn. Most of the taxes are paid after 2050, as the high investment rates combined with the rapid depreciation of assets reduce the taxable income in the build-out period.

Final commentary on main uncertainties

Our analysis is based on the best available information at the time of writing. SWEA has contributed with up-to-date information on offshore wind. There are a however number of uncertainties in any forecast spanning to 2050, such as demand developments, location of demand, cost developments for new technologies, offshore wind, and the hydrogen sector, and so on. Furthermore, it is important to emphasise, that all models, independent on how good and advanced they are, are always a simplification of reality.

Thus, the results and findings presented in this report do not reflect a final truth in any way, and should not be mistaken as a forecast or prediction, nor a normative statement. The study is however one of the most comprehensive and up to date in this field.