Clean and Affordable Norwegian Offshore Wind to Facilitate the Low-Carbon Transition

Kristina Haaskjold and Pernille Seljom

Abstract Norwegian offshore wind power can be a significant electricity supply contributor to facilitate the Norwegian and European green transition. The Norwegian government aim to grant concessions of 30 GW offshore wind within 2040, however, the realisation of this target depends on numerous uncertainties, related to e.g., future development in technology, national energy demand, the European power market, as well as social acceptance of energy production and grid expansion. This chapter analyses the role and cost-competitiveness of offshore wind to facilitate the low-carbon transition towards 2050. The energy system model, IFE-TIMES-Norway, is used to quantify the techno-economic capacity and distribution of offshore wind towards 2050, along with its impact on the overall energy system. Our results demonstrate that the ambitions of the Norwegian government can be economically viable without the necessity of subsidies, however, the outcome depends on the future development of the European power market. Moreover, the correlation of the Norwegian offshore wind resources is relatively weak between the northern and southern regions, as well as with Northern European countries. Less simultaneity enables an overall smoother production across Europe, which can enhance energy security. Further, results show that Norwegian offshore wind can play a central role in the decarbonization of end-use sectors by enabling greater hydrogen production from electrolysis.

Key Messages

- The Norwegian target of 30 GW offshore wind by 2040 is economically viable under certain market conditions.
- Norwegian offshore wind enhances the security of electricity supply in Norway and Europe (SDG 7).
- Offshore wind facilitates green hydrogen production and lower greenhouse gas emissions (SDG 13) and could contribute to new industry development (SDG 9).

K. Haaskjold (✉) · P. Seljom
Institute for Energy Technology (IFE), Kjeller, Norway
e-mail: kristina.haaskjold@ife.no; pernille.seljom@ife.no

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- Energy system models capture how offshore wind enables emission cuts in end-use.

1 Introduction

Norwegian offshore wind power can support the achievement of both Norwegian and European climate targets by providing new green electricity supply, as well as contributing to the political ambition to transform the Norwegian petroleum-based economy to be a value-creating and cost-competitive low-emission economy (Energi 21 2022). Consequently, offshore wind in Norway can contribute to the United Nations (UN) Sustainability Goals on "Affordable and Clean Energy" (SDG 7), "Climate action" (SDG 13) and on "Industries, Innovation and Infrastructure" (SDG 9). The role of offshore wind power in the transition of the Norwegian energy system is however highly uncertain. It depends inter alia on the future development of technology, the onshore Norwegian energy demand, the European power market, and the impact of climate change on renewable production. Further, a national market for offshore wind power is considered a prerequisite for the Norwegian industry to succeed in the international market (Afewerki et al. 2019). This chapter analyses under what conditions Norwegian offshore wind power is cost-competitive and can contribute to reaching the sustainability goals.

1.1 Motivation

Norway has a climate policy goal of reaching a low emission society in 2050 (Miljødirektoratet 2023). The largest sources of greenhouse gas emissions are the transport sector at 34%, with 16.4 million CO_2-equivalent, followed by the oil and gas production at 25%, with 12.2 million CO_2-equivalent in 2022 (Environment Norway 2022). As opposed to many other countries, there are negligible emissions from Norwegian electricity generation, which is primarily based on hydro- and onshore wind power. Consequently, offshore wind power will not directly contribute to lowering the emissions in the electricity sector but can facilitate the electrification of end-use sectors and the establishment of new green industries. For example, offshore wind can contribute to lowering emissions from oil and gas production in Norway, by replacing offshore gas turbines with electricity from offshore wind (Voldsund et al. 2023).

This study uses the long-term energy system model IFE-TIMES-Norway (Haaskjold et al. 2023), to analyse the role of offshore wind power in the decarbonisation of the Norwegian energy system. The cost-competitiveness of offshore wind power in 20 identified areas (Norwegian Water Resources and Energy Directorate 2023b) is analysed, taking into consideration the future uncertainty of demand and technology development. The future Norwegian energy demand is highly uncertain (Malka et al. 2023), where the electricity demand depends both on future activity and the degree of electrification in end-use sectors. However, the Norwegian Transmission System Operator (TSO), Statnett, expect a negative electricity balance from 2027 due to a projected increase in electricity consumption, without a corresponding increase in power production (Statnett 2022). One action that can reduce Norway's dependency on electricity imports is the ambition of the Norwegian government to grant concessions of 30 GW offshore wind by 2040 (Regjeringen 2022b). As a response, the Norwegian Water and Energy Directorate (NVE) (Norwegian Water Resources and Energy Directorate 2023b) identified 20 areas on the Norwegian continental shelf that have the potential to accommodate the 30 GW offshore wind power. However, as offshore wind power, particularly floating installations, is a technology that is under development, there are high uncertainties regarding the future costs and technology development (Shields et al. 2022).

The Norwegian government further stated that a significant share of the electricity from the 30 GW offshore wind power needs to be exported to other countries as it is too large for the Norwegian grid to accommodate (Regjeringen 2022a). At the same time, the Member States of the offshore grid corridor Northern Seas Offshore Grid (NSOG) have recently increased their targets for offshore renewable energy generation, with 60 GW by 2030 and up to 218 GW by 2050 (European Commission 2023). In this regard, it is important to understand the correlation between offshore wind power production in Norway and Northern Europe. A strong correlation makes it more profitable to use Norwegian offshore wind power to meet national electricity demand, store for future use, or produce other energy, such as hydrogen, rather than being exported or curtailed. On the other hand, a weaker correlation fosters higher offshore wind exports, reinforcing the energy security of northern European countries. Understanding the correlation between offshore wind areas within Norway is also important as it influences the need for other electricity generation and transmission to ensure the security of electricity supply.

The role of offshore wind power is also influenced by public acceptance, political preferences and legal and regulatory frameworks. (Linnerud et al. 2022), through a nationwide choice experiment with over 1612 individuals, examined how the general public's preferences for wind energy developments in Norway are affected by a shift from onshore to nearshore or offshore locations. The study concludes that respondents prefer offshore and nearshore locations to onshore ones. The social acceptance of new domestic transmission can also affect the offshore wind expansion, as transmission capacity expansion can be needed to match the offshore wind resources with Norwegian demand in various locations. According to a survey presented in (Aas et al. 2014), local acceptance of high voltage power lines in Norway was below the mid-point average. To proactively address the risk of public opposition of offshore wind, akin to the challenges faced by onshore wind (Korsnes et al. 2023), NVE has recently proposed several amendments to the administrative process for offshore wind, in particular to the Offshore Energy Act (Andersson et al. 2023). The amendments relate to the knowledge base and clarifications needed for the opening and allocation of areas for energy production at sea, the distribution of responsibility and tasks, and the content and structure of the concession process of energy production with associated grid infrastructure. The main goal of the proposal is to ensure (1) sufficient decision-making foundation, (2) efficient management processes that actively involve and consider public interest, and (3) increased predictability for project owners, which all aim to avert significant impediments to project progression. NVE also highlights the importance of harmonizing grid connection process with the licencing process for offshore wind.

1.2 Energy Modelling Literature

Numerous recent analyses have used power market models to address the cost-efficient integration of offshore wind power from a North Sea and Northern European perspective. For example, (Durakovic et al. 2023) use EMPIRE (Backe et al. 2022), a capacity expansion model of the European power market, to analyse how large-scale deployment of green hydrogen production affects the investments in transmission and generation in the North Sea area towards 2060. The analysis includes investment options in two of the 20 identified regions for offshore wind in Norway (Norwegian Water Resources and Energy Directorate 2023b). The chapter concludes that a high demand for green hydrogen will increase investments in offshore wind power, and that the North Sea will have a significant share of the total European electrolyser capacity, due to the favourable wind conditions. The authors suggest that further work should look more closely at national and regional analysis, to better incorporate national energy policies and strategies.

Another example is (Jåstad and Bolkesjø 2023) that uses the BALMOREL model (Wiese et al. 2018) to analyse the market value and economic potential of offshore wind developments for various grid connection strategies using the Norwegian continental shelf as a case. The analysis covers the Northern European power and heat market and includes offshore regions that are connected to four of the five spot price regions in Norway. By using Monte Carlo simulations, covering uncertainty in economic and political developments, 0–8.1 GW installed capacity can be economically attractive in Norway without any subsidy, when assuming a radial connection. Another result is that the market value is highest for offshore wind power when a plant has a hybrid grid connection to several markets compared to a radial connection to only one market. (Koivisto et al. 2020) also used the BALMOREL model to analyse the development of the electricity sector towards 2050 for the North Sea region with a focus on offshore wind power. Similarly to (Durakovic et al. 2023), the authors conclude that an increased electricity consumption, through sector coupling, is a more important driver for increasing offshore wind power installations.

(Reulein et al. 2023) uses the European energy system model, GENeSYS-MOD (Löffler et al. 2017), to address the influence of the introduction of 30 GW offshore wind in one of the 20 identified Norwegian offshore wind areas. The chapter concludes that the introduction of offshore wind capacity results in less capacity expansion of onshore wind and solar power. Note that in (Reulein et al. 2023), 30 GW offshore wind is a model assumption, whereas in our chapter we endogenize investments in offshore wind power and analyse under what conditions investments in Norwegian offshore wind is a techno-economic solution.

Compared to the described literature above, our analysis has a Norwegian perspective, providing a high detail level of the Norwegian energy system that includes interactions within the framework of sector coupling. In addition, we have identified three novelty contributions of our study.

- First, according to our knowledge, this is the first study that examines all the 20 identified offshore wind areas on the Norwegian continental shelf to analyse the cost-competitiveness of offshore wind. Thus, in contrast to the literature described above, we include a more detailed spatial representation of e.g., wind conditions, grid connections and onshore energy system integration. Moreover, this chapter quantifies the correlation of offshore wind resources between the 20 Norwegian regions and other Northern European countries.
- Second, we analyse the effect of offshore wind on Norwegian end-use sectors and emissions. By using a holistic energy system model that endogenies sector coupling and electricity demand, we quantify how offshore wind can contribute to electrifying and lowering emissions in end-use sectors. Although (Reulein et al. 2023) also used an energy system model, the results presented only focused on the electricity sector.
- Third, we analyse under what conditions Norwegian offshore wind power is cost-competitive, considering relevant uncertain parameters. In addition to the uncertainty on acceptance of onshore wind power technology development that is also included in (Jåstad and Bolkesjø 2023), we also include uncertainty on technology development of offshore wind, expansion of new transmission capacity and national demand under various development pathways of the European electricity market.

1.3 Research Questions

The overall objective of the chapter is to analyse the role of offshore wind power in the transition of the Norwegian energy system. In the conducted analysis, we address the following research questions:

- How is wind production from the 20 identified Norwegian offshore areas correlated, and how does this production align with offshore wind in the Northern European region?
- How does the cost-optimal investments in Norwegian offshore wind power depend on the development of future national demand, technology learning and subsidies, and on the European power market?
- How does Norwegian offshore wind power contribute to the Sustainable Development Goals (SDGs) on energy and climate, economy, and industry?

The outline of this chapter is as follows: Section 2 is devoted to the applied methodology, including a description of the TIMES model and model assumptions. Section 3 presents the corresponding results, whereas the conclusions are given in Sect. 4.

2 Methodology

First, this section presents the model structure and assumptions of the IFE-TIMES-Norway energy system model, including a detailed description of modelling of offshore wind. Second, we describe the analysed case studies and sensitivities and how they are quantified.

2.1 Energy System Model

The TIMES modelling framework is developed within ETSAP (the Energy Technology Systems Analysis Program), an implementing agreement of the International Energy Agency (IEA) during several decades (IEA-ETSAP 2023). TIMES is a bottom-up framework that provides a detailed techno-economic description of resources, energy carriers, conversion technologies and energy demand. TIMES models minimise the total discounted cost of the energy system to meet the demand for energy services for the analysed model horizon.

IFE-TIMES-Norway (Haaskjold et al. 2023) is a technology-rich model of the Norwegian energy system and is split into five regions corresponding to the current electricity spot price regions, NO1 to NO5. The model provides operational and investment decisions from the starting year, 2018, towards 2050, with model periods for every fifth year from 2020 to 2050. To capture operational variations in energy generation and end use, each model period is divided into 96 sub-annual time slices, where four seasons (winter, spring, summer, and fall) are represented by one day of 24 hours in each season. The model has a detailed description of end-use of energy, and the demand for energy services is represented by numerous end-use categories within industry, buildings, and transport. Each energy service demand category can be met by existing and new technologies using different energy carriers such as electricity, biofuel, hydrogen, and fossil fuels. Other input data include fuel prices, electricity prices in countries with interconnections to Norway, renewable resources, and technology characteristics such as costs, efficiencies, and availabilities.

Existing transmission capacity, both domestically and to European countries, is modelled exogenously and based on current capacity and ongoing capacity expansion. Moreover, the model allows for new investment capacity, both on existing and new connections. First year of investment is fixed to 2030 due to the long planning and construction process of building new transmission lines. The Norwegian electricity prices in the five spot regions are endogenous, as they are the dual values of the electricity balance equation. The electricity prices in countries with interconnections to Norway, including Denmark, Sweden, United Kingdom, Finland, Netherlands, and Germany, are a model input. Furthermore, these electricity trade prices are assumed to be independent of the traded quantities with Norway.

2.2 *Modelling of Offshore Wind*

The offshore wind modelling is based on the 20 identified offshore wind areas of NVE, that is illustrated in Fig. 1. The colour coding reflects the variations in wind conditions, in which green colour indicates the highest capacity factors (52–56%) and red indicates the lowest (46–47%). The power production potential for each area is provided by NVE as an hourly capacity factor for the period from 1951 to 2022 (Norwegian Water Resources and Energy Directorate 2023a). To adjust to the sub-annual temporal resolution of the model, we generate one normalized production profile for each offshore wind region consistent of four representative days (one for each season). The four days are chosen based on random selection of a subset of days, falling within a 50% span in standard deviation from the daily mean across all days within the period (1951 to 2022). The same days are used for all offshore wind regions to ensure consistency in production. The resulting profiles are shown in Fig. 4. These profiles are further scaled to hourly capacity factors by adopting the average capacity factor provided by NVE (Norwegian Water Resources and Energy Directorate 2023a), given in Table 1. Maximum expansion potential for each offshore wind area is assumed to be 2 GW by 2050 (40 GW in total). By 2030, 3 GW capacity is available for investments, corresponding to the two opened areas (Utsira Nord, located in Vestavind F, and Sørlige Nordsjø II, located in Sørvest F).

We assume that the areas that are located closest to Europe in the Southern North Sea, Sørvest A-E and Sønnavind A, can export electricity to Europe. For these connections, export to the United Kingdom (UK), Western Denmark, Germany and the Netherlands are included. These connections are hybrid, meaning that the cables can be used also for electricity trade between countries whenever offshore wind production does not exceed the cable capacity. Noteworthy, the invested capacity to European countries are limited by the invested capacity to Norway, meaning that radial connections to Norway need to be realized before investments in cables to Europe are made. This is reasoned by the Norwegian government's decision to only grant radial connections in the first development phase (Regjeringen 2022c). For the remaining offshore areas, the model can only invest in a unilateral connection to the adjacent spot region in Norway, as presented in Table 1. The investment costs for export cables are calculated based on the estimated kilometer distance to the various connection points.

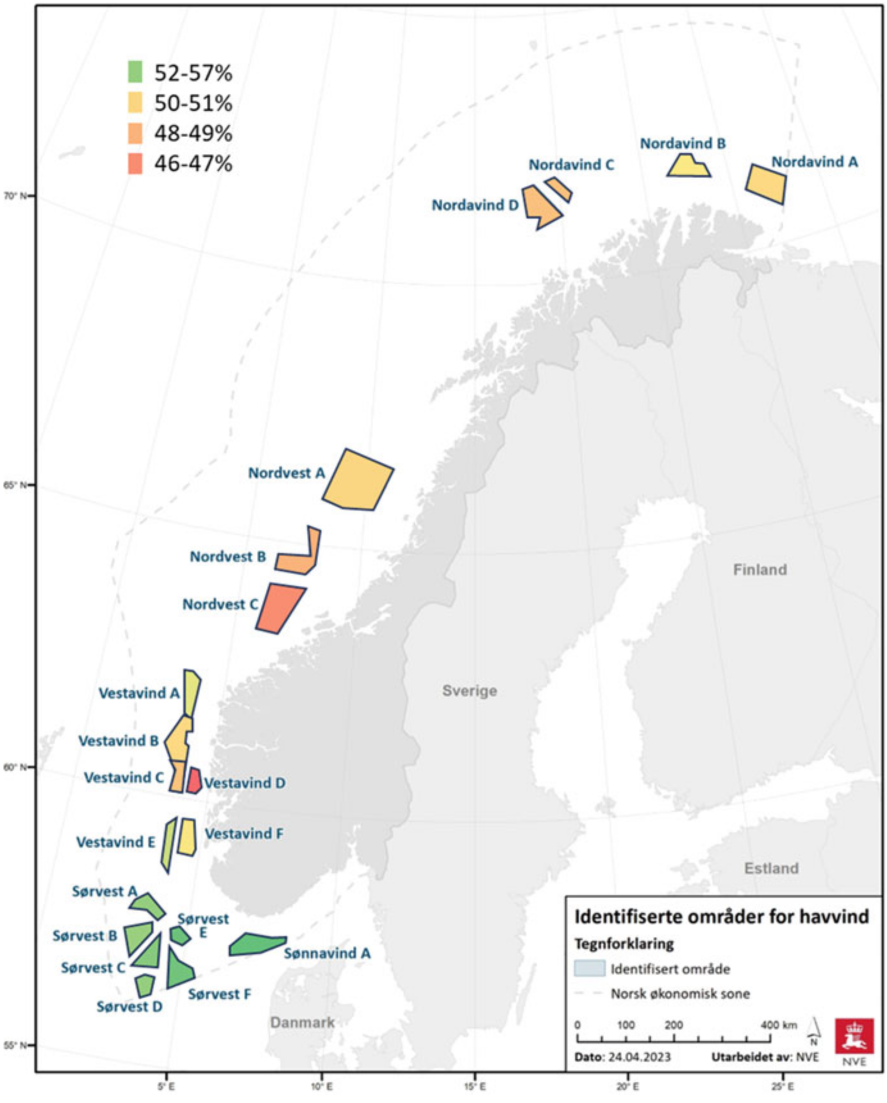

Fig. 1 Map of the 20 identified new areas for offshore wind development in Norway (Norwegian Water Resources and Energy Directorate 2023d). *Note*: Added color-coding to represent average wind conditions (Color figure online)

2.3 Case Studies and Sensitivity Analysis

To develop a robust analysis, different case studies and sensitivities have been examined to identify the parameters that have the largest influence on the investment in offshore wind power in Norway. All case studies assume a low-carbon society by 2050, with CO_2 price assumptions of 200 €/tCO_2 in 2030 and 438 €/tCO_2 in 2050, assuming a currency rate of 10 NOK/€. Three main parameters are chosen for the case studies:

1. **Investment cost of offshore wind**: For this study, a high (denoted "High") and a low (denoted "Low") cost case is used based on data provided by NVE (Norwegian Water Resources and Energy Directorate 2023c). The data differ depending on the foundation type and whether the connection to shore is alternating current (AC) or direct current (DC). Information for each area can be found in Table 1, with costs summarized in Table 2. Technology learning towards 2050 is assumed to be 15% (International Renewable Energy Agency (IRENA) 2019). In the

Table 1 Capacity factor, type of foundation and grid connection point for each offshore wind area (Norwegian Water Resources and Energy Directorate 2023b)

Offshore Area	Capacity factor (%)	Foundation	Grid connection point
Nordavind A	49.6	Floating	NO4
Nordavind B	50.2	Floating	NO4
Nordavind C	48.8	Floating	NO4
Nordavind D	48.8	Floating	NO4
Nordvest A	49.5	Floating	NO4
Nordvest B	48.3	Floating	NO3
Nordvest C	47.0	Floating	NO3
Vestavind A	51.3	Floating	NO3
Vestavind B	49.6	Floating	NO3
Vestavind C	48.9	Floating	NO5
Vestavind D	45.8	Floating	NO5
Vestavind E	52.3	Floating	NO2
Vestavind F	50.1	Floating	NO2
Sørvest A	54.5	Bottom-fixed	NO2, DK1, DE, NL, UK
Sørvest B	54.3	Bottom-fixed	NO2, DK1, DE, NL, UK
Sørvest C	55.1	Bottom-fixed	NO2, DK1, DE, NL, UK
Sørvest D	54.5	Bottom-fixed	NO2, DK1, DE, NL, UK
Sørvest E	56.1	Bottom-fixed	NO2, DK1, DE, NL, UK
Sørvest F	55.9	Bottom-fixed	NO2, DK1, DE, NL, UK
Sønnavind A	56.5	Floating	NO2, DK1, DE, NL, UK

Table 2 High and low investment cost projections used for the case studies (€/GW) (Norwegian Water Resources and Energy Directorate 2023c)

Type + connection	Low price projection		High price projection	
	2030	2050	2030	2050
Floating DC	3037	2581	4181	3554
Floating AC	3034	2579	4178	3551
Bottom-fixed DC	2140	1819	2756	2343

following, high technology learning refers to low investment costs, while low technology learning refers to high investment costs.

2. **Energy demand for industry and transport**: Two projections for future development in industry and transport demand is assumed based on (Aamodt Espegren et al. 2023). The high projection assumes an increase in industry demand of 69%, road transport demand of 37% and other transport demand of 14%. The low projection assumes a 1% increase in industry demand, while individual transport demand decreases by 10%.
3. **Electricity price in Europe**: Four price sets for European countries have been applied: (1) Reference prices based on linking with the European power market model EMPIRE (Haaskjold and Pedrero 2023), (2) high price set, with average price and volatility adjusted by 2, (3) low price set with average price and volatility adjusted by 0.8, (4) halved price set with average price and volatility adjusted by 0.5. The change in variability is computed by applying a square power transformation at each hour, resulting in lower lows and higher peak values.[1] The price profiles for a winter and a summer day in Sweden in 2050 for each price set are illustrated in Figs. 2 and 3.

The combination of parameters used in the case studies are presented in Table 3. In total, 10 cases have been analysed.

If not specified, investments in new land-based wind power and transmission capacity are a modelling option. To account for uncertainties related to social acceptance of such large infrastructure, a sensitivity analysis is also performed for each case combination in which no new land-based wind or domestic transmission cables can be built.

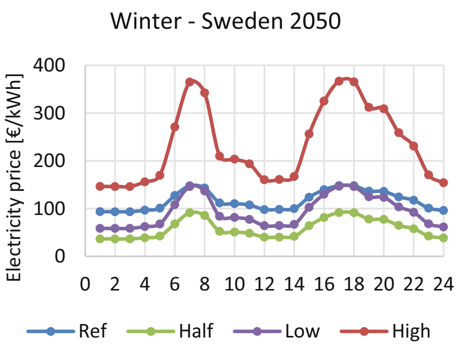

Fig. 2 Four price projections for electricity price development on a winter day in Sweden in 2050

[1] The squared values for each hour were normalized by the mean value of the transformed time series. These normalized profiles were then scaled by multiplying the mean value of the original price profile and a scaling factor corresponding to the desired increase/decrease in average electricity prices.

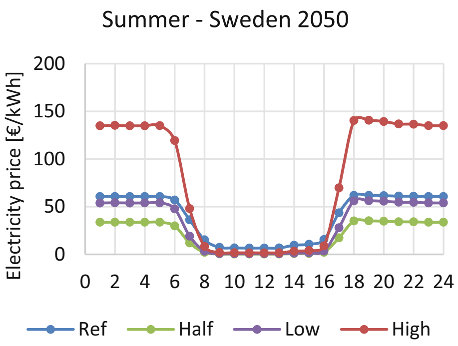

Fig. 3 Four price projections for electricity price development on a summer day in Sweden in 2050

Table 3 Combination of parameters for the case analysis

Name	Investment cost	Energy demand	Electricity price Europe
HH-Ref	High	High	Ref
LH-Ref	Low	High	Ref
HH-High	High	High	High
LH-High	Low	High	High
HH-Low	High	High	Low
LH-Low	Low	High	Low
HH-Half	High	High	Half
LH-Half	Low	High	Half
HL-Low	High	Low	Low
HL-High	High	Low	High

3 Results

First, this section presents the results of the Norwegian offshore wind resources used as input to the model, along with the correlation between offshore wind resources in Norway and neighbouring European countries. Second, the main results from the sensitivity analysis will be presented with focus on offshore wind investments and its impact on the Norwegian energy system.

3.1 Norwegian Offshore Wind Resources

As illustrated in Fig. 1, the average annual capacity factors for Norwegian offshore wind areas range between 46% and 57%. The areas located furthest south in Norway have the greatest wind conditions, with average annual capacity factors of 54–57%. Besides Sønnavind A, the areas in the south are also the ones mainly suitable for bottom-fixed foundation, entailing a significantly lower cost of investment. In addition to differences in annual production potential, the wind conditions across regions can also vary largely within a day and within seasons, as shown in Fig. 4.

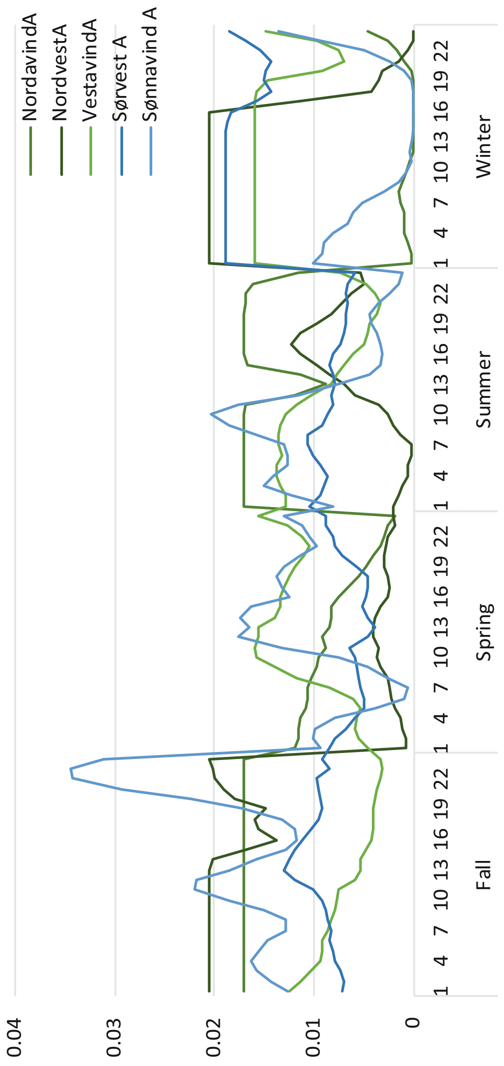

Fig. 4 Normalized capacity factors for five of the offshore wind areas, representing the hourly differences along the Norwegian coastline

While “Sørvest A”, “Vestavind A” and “Nordvest A” obtain maximum capacity factors during the winter, “Nordavind A” and “Sønnavind A” have almost no production in this period. This indicates that there is a smoothing effect among the areas that provide a more stable overall production.

Figure 5 illustrates the correlation between offshore wind areas in Norway and Northern Europe based on hourly resolution of wind data from 1951 to 2022. The results demonstrate that there is a low correlation in wind speeds between the various offshore areas in Norway. The correlation is below 0.5 for all instances, and in 7 out of 10 cases, the correlation is below 0.2. The highest correlation can be found between Sørvest A and Sønnavind A (0.5), which are located closer compared to the other areas.

Moreover, Fig. 5 also shows a weak correlation in offshore wind conditions between Norway and Europe. This applies especially for those located on the western and Northern part of Norway, in which correlation is below 0.25 for all instances. For Sørvest A and Sønnavind A, the correlation is slightly stronger, but still significantly lower compared to the correlation between the European countries. For example, correlation between Sønnavind A and Germany is 0.45, while that between Denmark and Germany is 0.81.

In further results, the offshore wind areas will be grouped according to their location, referred to as Nordavind (incl. A-D), Nordvest (incl. A-C), Vestavind (incl. A-F), Sørvest (incl. A-E) and Sønnavind (incl. A).

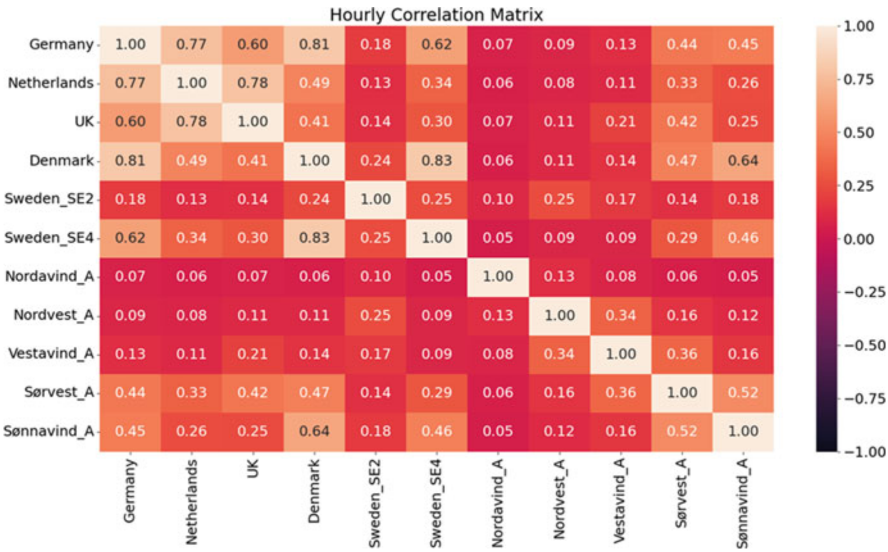

Fig. 5 Statistical correlation matrix with hourly time resolution for offshore wind areas in Norway and Northern European countries

3.2 Offshore Wind Investments

The results demonstrate that investments in offshore wind is highly dependent on the development of European electricity prices. Figure 6 shows the invested capacity for each offshore wind area for each of the ten case studies. With high electricity prices, the offshore wind capacity in 2040 ranges from 23 to 33 GW, whereas for the low price cases the capacity ranges from 12 to 28 GW. The case with highest capacity at 33 GW, has a production of 168 TWh, and occurs when the investment cost of offshore wind is low, and the national electricity demand is high.

The results indicate that the future technology learning and investment cost of offshore wind has a great impact on the invested capacity in 2040. Further, the impact of investment costs is more significant in the cases featuring lower electricity price levels in Europe. As shown in Fig. 6, compared to the low technology learning cases (HH-Ref and HH-Low), a higher technology learning gives additional 18 GW capacity in the reference price case (LH-Ref) and 16 GW capacity in the low price case (LH-Low). The significance of technology learning is further highlighted by the case with high investment costs and very low prices in Europe (HH-Half), in which no investments are made in offshore wind power.

Among the Norwegian offshore areas, the ones located in southern and western Norway are the most cost-competitive for offshore wind. These areas have the best wind conditions and are also located close to onshore regions with high demand and connections to the European power market. In the cases with low energy demand, investments are mainly concentrated in these areas, whereas investments are more

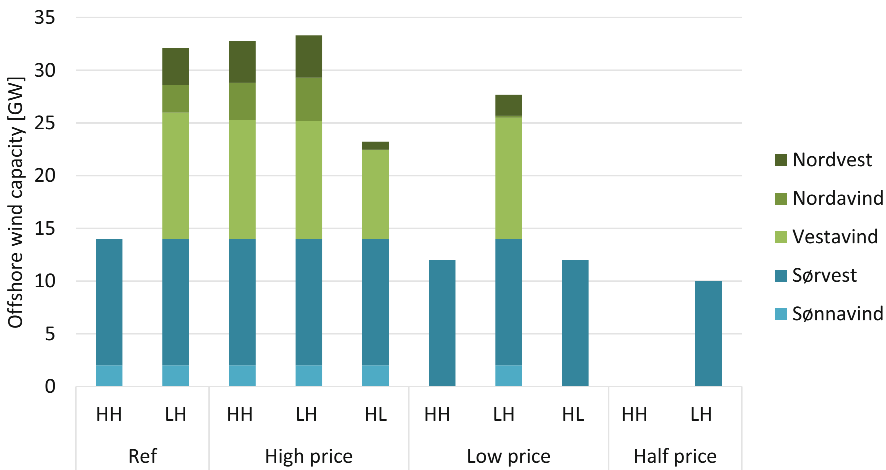

Fig. 6 Investments in offshore wind across all sensitivity cases and regions by 2040 (GW). *Notes*: *HH* High investment cost and High demand, *LH* Low investment cost and High demand, *HL* High investment cost and Low demand

widely distributed across areas in cases with high energy demand. Consequently, the future electricity demand in Norway influences the offshore wind deployment.

3.3 Electricity Production and Use

Among the electricity generation technologies, offshore wind investments have the largest impact on investments in building applied PV (BAPV) and hydropower. This is illustrated in Fig. 7 that shows electricity generation by technology from new investments by 2050, comparing cases with high and low investment cost of offshore wind across different European price levels. Note that utility PV is not included as an investment option. The impact on hydropower is largest in high price cases (LH-High), with an 8% reduction in production compared to the high investment cost case (HH-High). Moreover, the flexible hydropower shifts production from winter to summer months to accommodate offshore wind production. The impact on PV investments is reduced the most in the low-price case (LH-Low), with a 40% reduction compared to the high investment cost case (HH-Low). This can be explained by the correlation between PV production and periods of low electricity prices in Europe. With zero prices during mid-day hours (as illustrated in Fig. 3), the market value of offshore wind becomes relatively higher compared to that of PV. Finally, since onshore wind is a highly cost-optimal solution in Norway, the production is identical for all cases, and is thus independent of the offshore wind investments.

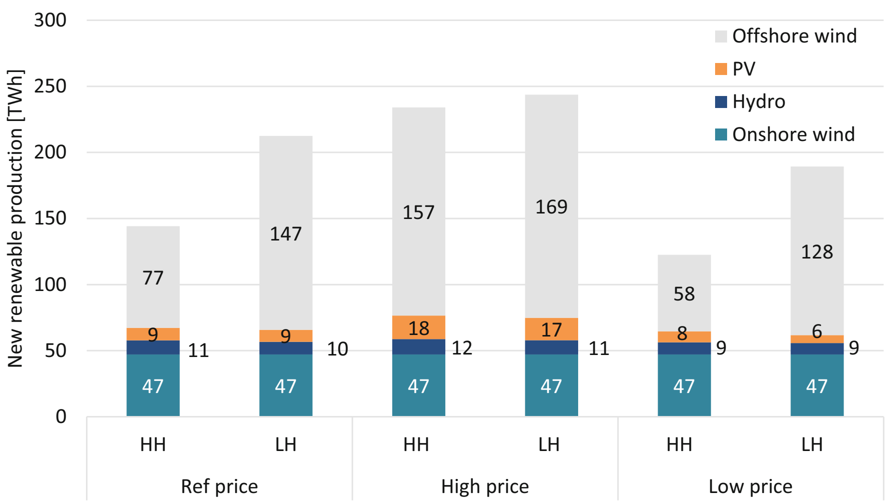

Fig. 7 New renewable production by energy source for 2050. *Notes*: *HH* High investment cost and High demand, *LH* Low investment cost and High demand

The electricity generation mix influences the long-term marginal cost of electricity in Norway. The results indicate that higher technology learning for offshore wind power, which lowers the investment costs and increases offshore wind investments, lowers the average electricity price in Norway. The cases with low investment costs have 5–8% lower average Norwegian electricity prices in 2050 compared to the cases with higher investment costs. Further, the impact on electricity prices varies between the Norwegian spot price regions. With low European prices, the price impact is highest in the spot price regions of Oslo and Bergen, NO1 and NO5, decreasing with 6–8%, whereas with high European prices, the electricity price is reduced most in the spot price regions of Trondheim and Tromsø, NO3 and NO4, with a 28% reduction.

For end-use, offshore wind primarily affects the use of electricity for hydrogen production. Figure 8 illustrates the electricity use per sector in 2050, comparing cases with high and low investment cost of offshore wind. The impact is largest in high price cases, where lower investment cost of offshore wind (LH-High) results in a 40% increase in hydrogen production compared to the high investment cost case (HH-High). With low electricity prices, the total electricity use is the same independent on investment cost of offshore wind. For the other sectors- building, district heat, industry and transport- offshore wind investments have negligible impact on electricity use.

The increased hydrogen production, resulting from offshore wind power, decreases the Norwegian CO_2 emissions. Lower investment costs of offshore wind result in a 3% decrease in emissions compared to higher investment costs in the high price case. In the latter, the hydrogen production from electrolysis is mainly substituted by blue hydrogen (92%), however the overall production level is still reduced. The reduction can be found in mainly sea transport. Higher investment

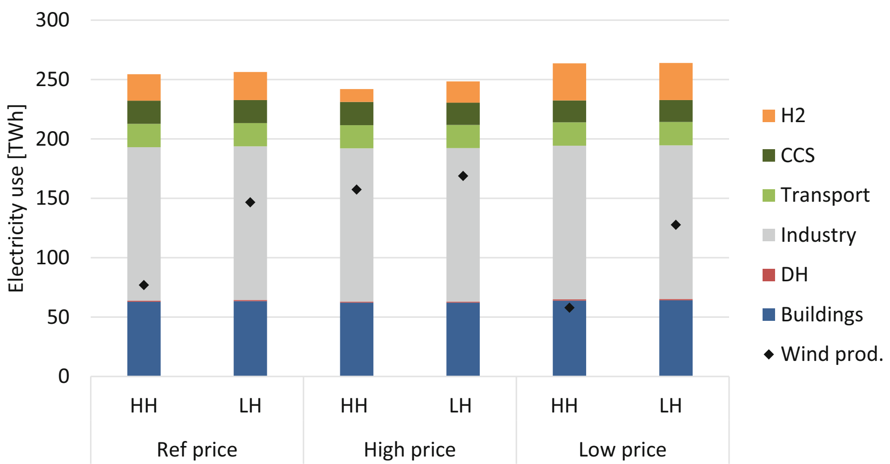

Fig. 8 Electricity use per sector for 2050. *Notes*: *HH* High investment cost and High demand, *LH* Low investment cost and High demand

costs result in a 7% reduction in use of hydrogen and ammonia, which is substituted by Marine gas oil (MGO).

3.4 Electricity Trade

Large scale deployment of offshore wind increases the net electricity export from Norway, as illustrated in Fig. 9. However, the net electricity trade is highly dependent on both the electricity price development in Europe and the costs associated with offshore wind investments. For both cases featuring high electricity prices, Norway is a net exporter in 2050, with a 10% increase in electricity exports under the conditions of low offshore wind investment costs (LH-High). The impact is substantially greater under low European price levels, where higher technology learning of offshore wind results in a shift from net import volumes of 14 TWh (HH-Low) to net export volumes of 48 TWh (LH-Low). In this case, Norway becomes a net exporter also from an onshore perspective, thereby increasing national security of electricity supply. The volumes directly exported from offshore regions to Europe ranges from 30 TWh (HH-Low) to 56 TWh (LH-High). Consequently, the total net export volumes from onshore and offshore Norway can potentially reach 104 TWh (LH-High). Noteworthy, this study assumes political support for hybrid connections for all offshore wind areas in the southern North Sea, hence allowing electricity to be transmitted between European countries in hours of lower offshore wind production. As emphasized by (Jåstad and Bolkesjø 2023), this assumption increases the profitability of offshore wind investments.

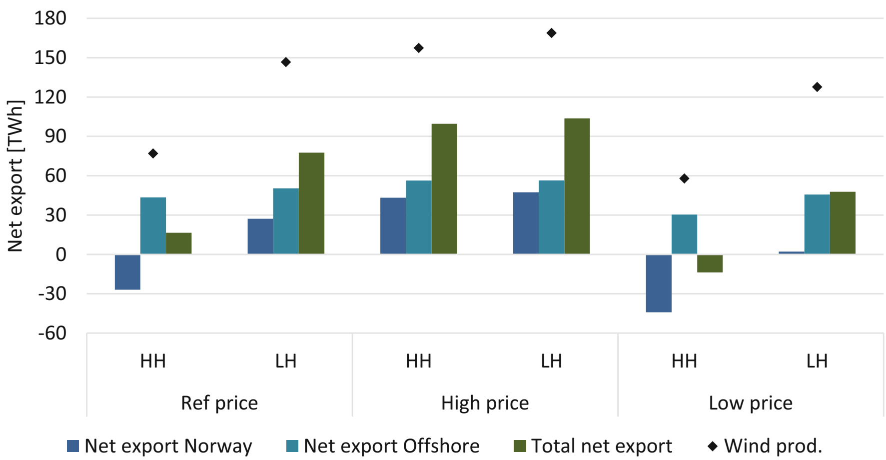

Fig. 9 Net export of electricity from onshore and offshore Norway in 2050. *Notes*: *HH* High investment cost and High demand, *LH* Low investment cost and High demand

3.5 *Sensitivity on Acceptance for Onshore Wind and Transmission Cables*

The results demonstrate that acceptance of new domestic transmission cables and onshore wind affects the investments in offshore wind capacity, but mainly in the northern offshore regions. Figure 10 shows the difference in invested capacity when no new investments in transmission cables (HH-T and LH-T) and onshore wind (HH-O and LH-O) are allowed, compared to the cases with no limitations (HH and LH). The impact of limiting expansion of domestic transmission cables is negligible, with reductions of 130–640 MW. On the other hand, limiting onshore wind investments has a greater impact, with 2.6–5.3 GW increased capacity in offshore wind in all cases except HH-O-Low. In this case, the high investment cost and low European prices makes additional offshore wind investments unprofitable, and Norway relies on imports instead. In cases where offshore wind investments increase, it does not completely offset the initial investments in onshore wind, falling short of about 5–8 GW. In the high price cases (HH-O-High and LH-O-High), the maximum expansion potential assumed for offshore wind is reached at 40 GW. In low price cases (HH-O-Low and LH-O-Low), there is still additional investment potential to be utilized. The total decrease in energy production due to limitations on onshore wind range from 7 TWh (LH-O-Low) to 32 TWh (HH-O-Low). Consequently, Norway becomes increasingly more reliant on Europe in such a restrictive situation.

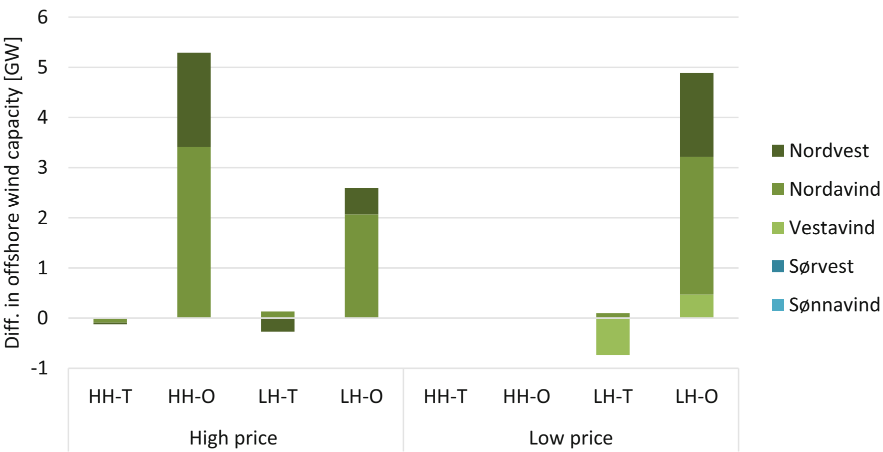

Fig. 10 Difference in offshore wind capacity when limiting investments in new transmission cables (T) and onshore wind deployment (O), compared to HH and LH case. *Notes*: *HH* High investment costs, High demand, *LH* Low investment costs, High demand, *T* No new domestic Transmission, *O* No new Onshore wind

4 Conclusion

This study analyses the role of offshore wind power in the decarbonisation of the energy system towards 2050. First, we have quantified the correlation of electricity production between the 20 identified Norwegian offshore wind areas and areas in Northern Europe. Second, we have used a long-term energy system model to analyse techno-economic investments in Norwegian offshore wind given different uncertain parameters, including European electricity prices, technology learning rates and national energy demand. Third, we have analysed how offshore wind power production influences the Norwegian energy system, including the impact on investments in other electricity generation technologies, the electricity use and emissions and the electricity trade. Finally, we have investigated how acceptance for expansion of domestic transmission cables and onshore wind power in Norway influences the techno-economic investments in offshore wind power.

To summarise the results, we answer the research questions of our chapter below.

Research question 1 How is wind production from the 20 identified Norwegian offshore areas correlated, and how does this production align with offshore wind in the Northern European region?

The annual average wind capacity factors for the 20 areas range from 46% to 57%, with the most favourable wind conditions in areas located furthest south in Norway. On an hourly basis, the wind production varies largely across the coast, with a weak correlation below 0.2 between the north and the south. Additionally, offshore wind in Norway is weakly correlated with offshore wind production in Northern Europe. Consequently, a large share of offshore wind power distributed along the Norwegian coast and across Northern Europe can reduce the risk of energy shortages through a smoothing effect, thereby enhancing resilience while promoting a low-carbon development of the energy system.

Research question 2 How does the cost-optimal investments in Norwegian offshore wind power depend on the development of future national demand, technology learning and subsidies, and on the European power market?

The future technology learning in offshore wind technology and the price development of the European power market has a large impact on cost-optimal investments in offshore wind in Norway. The results show that in a future European market characterized by medium to high electricity prices, the ambitions of the Norwegian government of 30 GW capacity by 2040 become economically viable without the necessity of subsidies. With lower European prices, techno-economic investments are lowered to 0–12 GW unless subsidies or sufficient technology improvements are realized. The largest investments are made in the southern and western parts of Norway, where energy demand is the largest and the distance to Europe is closest. Moreover, lower national energy demand generally decreases investments in offshore wind with a higher concentration of capacity in the south. Limitations on onshore wind expansion have the opposite effect, increasing offshore investments in most cases. Finally, expansion of domestic transmission capacity has a negligible impact on investments in offshore wind.

Research question 3 How does Norwegian offshore wind power contribute to the Sustainable development goals (SDGs) on energy and climate, economy, and industry?

Norwegian offshore wind can contribute to reducing both Norwegian and European climate emissions (SDG 13) by providing green electricity (SDG 7). This study shows that offshore wind investments increase Norwegian green hydrogen production from electrolysis, enabling emission reductions in Norway due to the substitution of blue hydrogen and MGO. Moreover, results indicate that the flexible Norwegian hydropower is a facilitator for increased offshore investments, providing an advantage that many other European energy systems are lacking. Offshore wind can also be beneficial in ensuring a diverse energy mix, in which the complementarity between offshore wind and PV enables mitigation of the cannibalization effect of PV occurring during mid-day hours. As shown by the results, offshore wind can lower the average electricity price in Norway by 6–8%, and even more on a regional basis, and hence contribute to affordable electricity for both individuals and businesses.

Norwegian offshore wind can further facilitate the green transition in Europe (SDGs 7&13), however, the supply of electricity depends largely on European electricity prices and technology development. Low investment costs play an important role in altering net-import situations that could occur in futures characterized by low electricity prices. In general, results show that offshore wind can help to ensure the security of electricity supply in Norway while simultaneously providing electricity to Europe in hours of high production. Noteworthy, this study is limited to the optimization of the Norwegian energy system, and we are therefore not able to quantify the impact on emission reductions as a result of Norwegian offshore wind export to Europe. Nevertheless, the analysis finds a weak correlation to Europe, indicating that offshore wind power from Norway could reduce dependency on fossil fuels when wind conditions are limited in Northern Europe. Further work will aim to quantify the impact and support of European climate targets by integrating European and national energy system models.

Norwegian offshore wind can also enable the electrification of industry and new industry development (SDG 9). In this study, two levels of future activity level have been analysed. Results indicate that even in cases with high national demand, large volumes of electricity export could be realized. Consequently, offshore wind investments could enable even larger economic growth than assumed in this study. Further, Norwegian offshore wind can contribute to transform the Norwegian petroleum-based economy to be a value-creating and cost-competitive low-emission economy. To quantify the effect on the economy, it is an option to link energy system models to general equilibrium models.

There are several other **further research needs** related to providing robust insights on the role of offshore wind in the energy transition. This includes analysing the robustness of the investment strategy given a high temporal resolution, different climate years, climate change effects, and forecast errors. Different regulatory frameworks governing offshore wind will also impact the deployment. To evaluate how Norwegian offshore wind can contribute to a fair green transition, the implications of the recently proposed Norwegian amendments to the regulatory processes of the Offshore energy act should be analysed.

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