NTRANS
Norwegian Centre for Energy Transition Strategies

FORSKNINGSSENTER FOR MILJØVENNLIG ENERGI
Norges forskningsråd

Integration of offshore wind power at Utsira Nord and Sørlige Nordsjø II

Case study on effects for Norwegian stakeholders

Vegard Viken Kallset[1], Stefan Jaehnert[1]

[1]SINTEF Energy Research

Working paper 04/2021

ISBN 978-82-93863-10-6

Introduction

In June of 2021 the Norwegian government put forth a report to the Parliament called 'Energi til arbeid' (Olje- og energidepartementet, 2021) regarding Norway's position as an energy producing nation. Future development of offshore wind power is highlighted as an opportunity Norway in the upcoming decades, both for supplying additional renewable energy domestically and for developing industry in a growing market.

As a step in realizing this opportunity, in June of 2020 the government opened two offshore areas for offshore wind farms: Utsira Nord and Sørlige Nordsjø II. The interest from the industry in developing projects for these areas is significant; as of August 2021, 13 consortiums have announced a desire to build in or both areas (Øvrebø & Øystese, 2021). Potential offshore windfarms in these areas could be connected directly to Norway, another nearby European country where the electricity prices are higher, or with some combination where the offshore wind farm also functions as an offshore hub. How these alternatives impact the Nordic power system and which of them is the most the most societally beneficial alternative is uncertain.

Several studies have previously examined potential North Sea grids. (Farahmand, Huertas-Hernando, Warland, Korås, & Svendsen, 2011) showed that meshed solutions achieve lower costs compared to radial solutions over the lifetime of the projects and (Kristiansen, Korpås, & Farahmand, 2018) demonstrated that a Power Link Island would achieve cost savings of 15,8% compared to traditional radial typologies. Additionally, (Gea-Bermúdez, Pade, Juhani Koivisto, & Ravn, 2020) find that a good grid topology and sufficiently long planning horizon is important to minimize system costs.

In the report 'Energi til Arbeid' an analysis from NVE is included where they examine a wind farm at Sørlige Nordsjø II and alternatives for connection to Norway or Great Britain. In their calculations none of the alternatives with an offshore windfarm has a positive effect on social welfare. However, the assumptions made in the calculations could have a significant impact on the results.

In this analysis we have done a similar calculation with four cases for offshore wind farms. Three of them looks at alternatives for connecting a wind farm at Sørlige Nordsjø II to either Denmark, southern Norway or to both with an offshore hub. The fourth case explores the impact of a wind farm at Utsira Nord with a connection to Norway.

This paper aims to explore how the impact of building an offshore wind farm will be different depending on how it is connected to the existing grid. In chapter 2 the dataset and the four cases are described in further detail. Then, the economic results of the cases are presented and compared in chapter 3. Finally, chapter 4 discusses the impacts of historical weather years, infrastructure investment costs and effects on stakeholders.

Dataset

The underlying dataset for the case studies is developed in the FME HydroCen IPN New environmental constraints - consequences for the power system[1]. It covers Northern Europe with a different level of details for the various countries and represents a reference scenario for 2030. This reference scenario has conservative assumption on the development of renewable energy in the European power system. However, using this conservative scenario is expected to show larger effects of new offshore wind park installations. Hence, it will be easier to use such results for the evaluation of the case study.

In the following a short overview on the main input assumptions is provided. As a starting point for building the scenario, the aim was to base input parameters as much as possible on open sources, to be able to provide a transparent background. The main exogenous inputs are forecasts for future fuel and CO2 prices, power demand levels as well as the infrastructure development of the power system. The development of the demand for the Nordics is based on expectations provided by NVE and the European commission, assuming an increase by 5% to 15% in the different countries

Furthermore, the following exogenous prices are defined to be the same as in Statnett's long term market analysis (Statnett, 2021):

- Coal 70 $/t
- Gas 20 EUR/MWh
- Biofuel 30 EUR/t
- CO2 70 EUR/t

Regarding the infrastructure of the power system, a partial phase out of nuclear power plants and coal power plants is assumed, leading to a reduction of dispatchable capacity. On the other side, no significant expansions of hydropower in the Nordics are included, assuming that the hydropower system is similar to today's system regarding the installed generation capacity in the water courses. Within the transmission system, cross-border interconnectors that are under construction and planned (included in ENTSO-E's Ten-Year-Network-Development-Plan) are accounted for, which among others comprises the NordLink and NSL HVDC cables. Furthermore, the expansion of the Western corridor in Norway is taken into account.

Case description

The following cases are analysed with power market simulator EMPS. EMPS is a long-term optimization model made for operational use in hydro-dominated power systems. It takes uncertainty of inflow and variable renewable energy sources into account and calculates water values for each area, which represents the alternative cost of water. The water values are then used in a calculation to determine the optimal dispatch for thermal and hydro power plants in the system. A more detailed description of EMPS can be found in (Wolfgang, et al., 2009).

Case 1 – Sørlige Nordsjø II with connection to Denmark:

The case aims at identifying the economic potential of offshore wind in the North Sea and the potential of exporting flexibility from Norwegian hydropower to back up wind power in the North

[1] NFR 309622

Sea regions. The assumption in this case is an expansion of offshore wind power in the block "Sørlige Nordsjø II" with 3GW in line with the maximum allowed capacity for this area. For the wind park a connection to Denmark is assumed. In addition, there are HVDC cable(s) from Norway to Denmark. The main objective is to evaluate the effect of transmission bottlenecks and the extra economic potential for Norwegian hydropower. A specific point to assess is the difference in resulting price variability in Denmark and Norway resulting from the offshore wind power expansion.

Case 2 – Sørlige Nordsjø II with connection to Norway:

The main difference to Case 1 is that the offshore wind park is directly connected to Norway. The focus in this case compared to case 1 is the improved access for Norwegian hydropower to provide necessary flexibility to back up the offshore wind power generation capacity. Furthermore, the case sheds light on the potential of combining operation of offshore wind power and Norwegian hydro power and the effect of additional power fed into the Norwegian power system.

Case 3 – Utsira Nord with direct connection to Norway:

The case Utsira Nord will assess the effects of a combination of Norwegian hydropower and offshore wind power, located rather near to the coast. The offshore wind park has an installed generation capacity of 1.5 GW and is directly connected to the Norwegian power system within one of the market areas (NO2 or NO5). In this case the investment costs required for the wind farm will be higher per MW, because it will be necessary to use floating wind turbines.

The evaluation of this case will target the change in price structure, and the price level.

Case 4 – Sørlige Nordsjø II as offshore hub:

The offshore hub case addresses a possible construction of connections from the block "Sørlige Nordsjø II" to Norway and to Denmark, establishing an offshore hub in the North Sea. The focus in the case is on the assessment of the additional economic potential with a two-ways connection and impact on the potential for Norwegian hydropower. This connection is a 1500 MW HVDC cable to Denmark as well as to Southern Norway, while the capacity of the wind farm is still 3 GW.

In addition to the four upper cases, results for the reference scenario are presented.

Results

Price characteristics

Table 1 shows both average price and the average of yearly standard deviation for the areas Sorland, Vestsyd and Denmark West in each of the cases. The cases where the area is directly connected to the offshore wind farm is highlighted in the table.

TABLE 1 AVERAGE PRICES AND AVERAGE STANDARD DEVIATION

	Average price			Average standard deviation		
	Sorland	Vestsyd	W Denmark	Sorland	Vestsyd	W Denmark
Reference	49.02	48.6	57.49	8.4	8.38	32.52
Case 1	47.59	47.27	51.81	9.2	9.17	30.05
Case 2	43.46	44.75	56.4	10.69	10.61	32.73
Case 3	47.06	46.55	57.05	9.52	9.44	32.6
Case 4	47.41	47.81	51.08	9.05	8.7	23.8

Generally, the addition of an offshore wind farm lowers the total price level, relative to the reference case. Also, the price levels of the areas directly connected to the wind farm are more impacted than the others. Case 3 stands out as not having as large effects as the other cases on the price. This is mainly because the wind farm is smaller in this case. However, it might also be because the wind farm is connected further into Norway in this case, enabling the flexibility of hydropower to better make up for the increased wind.

The standard deviation generally increases with the addition of the offshore wind farm. The intuitive explanation for this is that more variable production in the system leads to higher price variability. Here, the exception is when the wind farm is connected to Denmark. In case 2 and case 4 the standard deviation of Denmark decreases relative to the reference case. This might be happening because the additional energy helps alleviate energy shortage in some cases.

In Figure 1, percentile plots of the prices in the various weather years are presented for Sorland in the reference case and in case 2. It is apparent that the overall price level is lower and that the

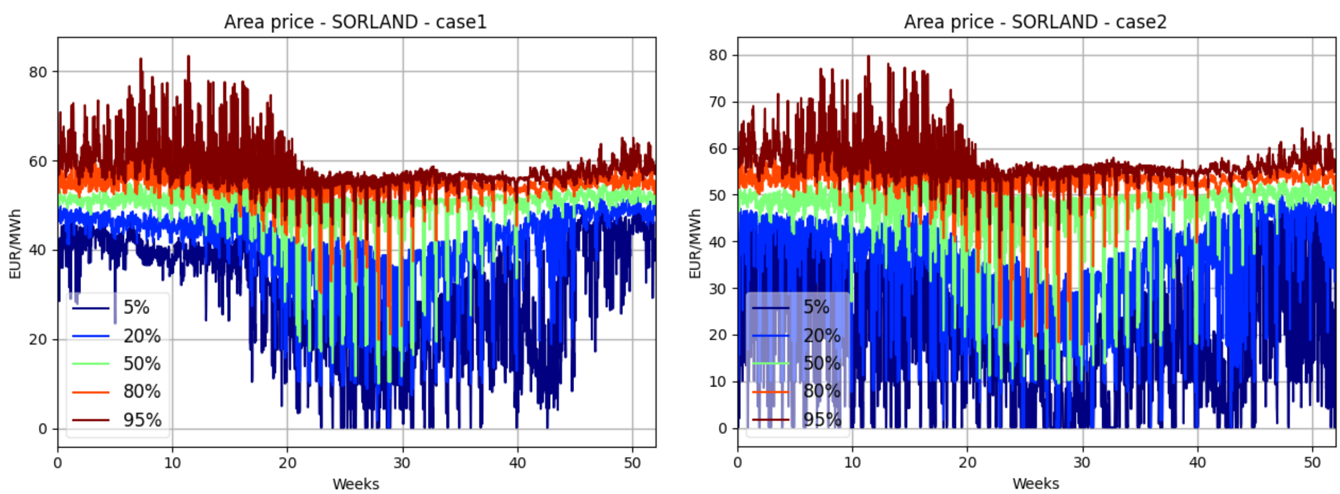


FIGURE 1 PERCENTILE PRICE IN SORLAND FOR BASECASE AND CASE 2

differences between the weather years are increased. For the wet years, price dips towards zero is much more frequent when the wind farm is connected to Sorland.

Comparing the prices in case 1 and case 2, we see that where the offshore wind farm is connected has a large impact on the prices in both Norway and Denmark. In Sorland the prices are about 4 EUR/ MWh lower in case 2, while in Vestsyd they are about 2.5 EUR/ MWh lower. This shows that the effects of the wind farm also impact other areas in Norway, though not so much as at the connection point.

In case 3, the wind farm is also connected to Norway, but since it is built at Utsira-Nord instead of in Sørlige Nordsjø it is connected to Vestsyd instead of Sorland. The installed capacity is also lower because the capacity that has been opened for so far in Utsira Nord is lower than at Sørlige Nordsjø II. The result is that total production of the wind farm is about 5.2 TWh in case 3, while in case 1, 2 and 4 it is around 11 TWh. This reduced production is reflected in the fact that the prices are 1.6, and 1.8 EUR/MWh higher in case 3 than in case 2 for Sorland and Vestsyd respectively.

In case 4 both Sorland and Western Denmark is connected to an offshore hub. In this case the price in Denmark is even lower than in the case where it is connected to only the wind farm. This is because the price level in Sorland is lower than the price level in Western Denmark and contributes to further lowering the price. In Sorland the price is lowered by being connected to the wind farm but increased by being more closely connected to Denmark. The result is a price that is higher than in case 2, but lower than in the reference case.

Economic results

Even though the offshore windfarm creates revenue, the extra injected power also leads to lower prices which impact other stakeholders in the system. This gives lower producer surplus for hydropower and higher consumer surplus. How big these consequences are depends on the case, as can be seen in

Table 2. The largest reduction in hydropower revenue is seen when the wind farm is connected to only Norway in case 2 and in case 3.

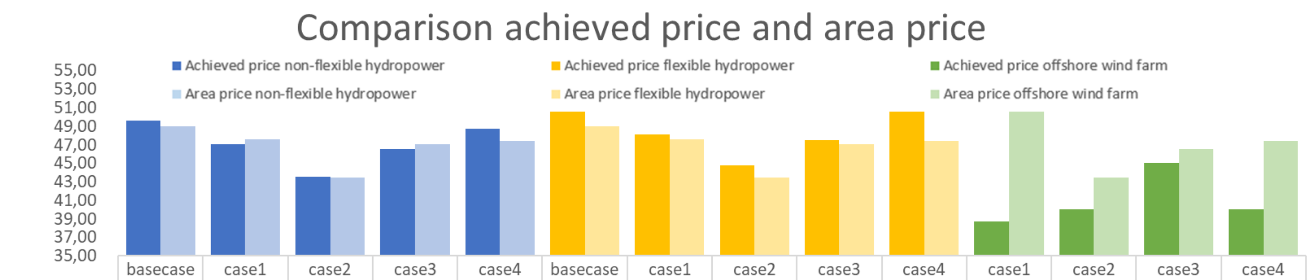
TABLE 2: CHANGE IN YEARLY PRODUCER SURPLUS AND CONSUMER SURPLUS RELATIVE TO THE REFERENCE CASE

	PRODUCER SURPLUS			**CONSUMER SURPLUS**	
	Hydro Sorland [kEUR]	Hydro Vestsyd [kEUR]	Offshore windfarm [kEUR]	Norway [MEUR]	Denmark [MEUR]
CASE 1	-31 998	-21 880	569 554	185	194
CASE 2	-100 206	-62 471	474 719	517	45
CASE 3	-40 047	-31 273	246 700	249	19
CASE 4	-13 000	-2 261	544 590	125	244

Achieved price

Figure 2 shows the achieved price for two hydro plants and the offshore wind farm in each case, along with the price in the area which the plant is located. The two hydro power plants are chosen such that one of them is highly flexible, and the other is less flexible. The flexible hydro plant achieves the highest price since it will only produce when the price is high. The offshore wind farm, on the other hand, is not able to adjust its production to the price, and therefore gets the lowest achieved price. The wind farm also gets lower prices because it is not connected directly to the area, but through a cable with losses.

The offshore wind farm gets its highest achieved price in case 3, where it is located at Utsira Nord. Nevertheless, since the installed capacity is higher at Sørlige Nordsjø II, the revenues for the offshore wind farm are highest in case 4. The value of combining intermittent wind power with flexible hydro can be seen from the fact that even though the average price in western Denmark is higher than in southern Norway, the achieved price for the offshore wind power plant is higher when it is connected to Norway.



	Non-flexible hydropower					Flexible hydropower					Offshore wind farm			
	basecase	case1	case2	case3	case4	basecase	case1	case2	case3	case4	case1	case2	case3	case4
Achieved price	49,60	47,02	43,58	46,54	48,73	51,42	48,12	44,77	47,53	51,24	38,74	40,06	45,02	40,07
Area price	49,02	47,59	43,46	47,06	47,41	49,02	47,59	43,46	47,06	47,41	51,81	43,46	46,55	47,41
Difference	0,58	-0,57	0,12	-0,52	1,32	2,40	0,53	1,31	0,47	3,83	-13,07	-3,40	-1,53	-7,34

FIGURE 2 COMPARISON ACHIEVED PRICE AND AREA PRICE

Discussion

Historical weather years

Figure 3 plots the hydropower production for the historic weather years. Within the figure it can be observed, that especially in the 1960 and 1970 occurred rather dry years with low hydropower production, while there is substantially higher production after the year 2000. This might be due to climate change. The same applies to windpower production, which varies significantly from year to year.

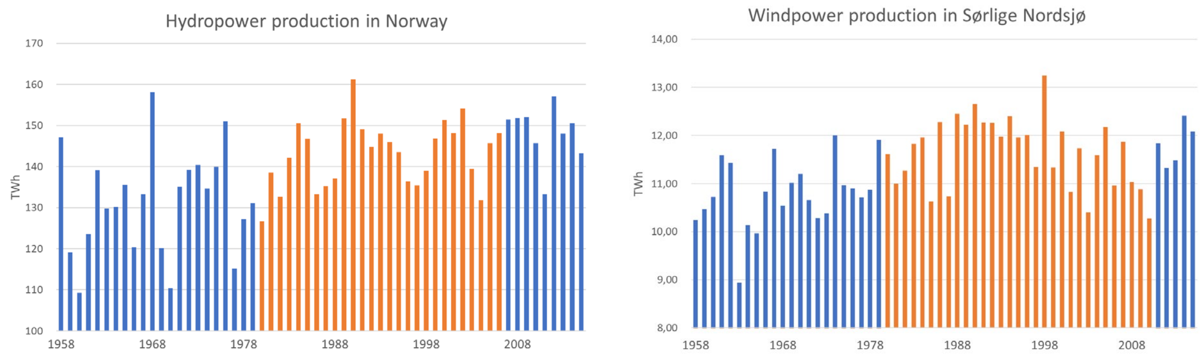


FIGURE 3: HYDROPOWER AND WINDPOWER PRODUCTION FOR HISTORICAL WEATHER YEARS (NORMAL PERIOD 1981-2010 MARKED IN ORANGE)

Hence, it is important to evaluate the historic period which is used for the inflow, wind, and solar time series. These have a high impact on the results. In the analyses presented here, it is chosen to use the period of 1981-2010 (marked orange in the above figure), which is used by NVE as their normal period. In general, when using the normal period, average prices are lower, which is due to neglecting the period with dry years.

The analysis presented in this paper examines a 'normal' year. However, as discussed in (Jaehnert, Korpås, Doorman, & Hyldbakk, 2015) the annual variability of renewable energy sources ensures that the results from year to year might be significantly different. For the power system as a whole, the increased energy from wind will reduce the shortage of energy in the driest years and reduce the risk of load shedding. For the investors of the wind farm the variable production introduces an additional risk.

Infrastructure investment costs

The results presented above all exclude the investment costs, which occur in the various cases. These are mainly the costs for constructing the offshore wind farm as well as the HVDC interconnectors.

Investments costs for offshore wind projects are currently about 1.5-2.5 MEUR/MW for fixed foundation turbines, with an expectation of further cost decline. Hence, a good assumption for further discussion is certainly 1.5 million EUR/MW. It is more difficult to estimate the cost of a wind farm based on floating turbines, as the technology is less mature. It is likely that floating wind will remain more expensive than fixed foundation turbines, so an estimate of 2 million EUR/MW is used for Utsira Nord in case 3.

To estimate grid investment costs the formula and cost parameters from (Til Kristian Vrana, 2018) has been used. These costs consist of cable costs and the costs of offshore and onshore HVDC. Of these, the costs of the HVDC nodes, and especially the offshore nodes are the most significant. The assumptions for the offshore installations therefore have a large impact on the overall results.

The required investments for case 1, 2 and 3 is straightforward as the cable consist of a single connection between the offshore windfarm and land. For case 4 the cost of the cable is same as in case 1 and 2, even though the windfarm is connected to both Denmark and Norway. This is because the capacity is 1.5 GW in either direction rather than 3 GW. However, some increased costs should nevertheless be expected because of the added complexity of connecting to two countries. Therefore, the number of offshore nodes was set to 1.5 in case 4, rather than 1 as in the other cases

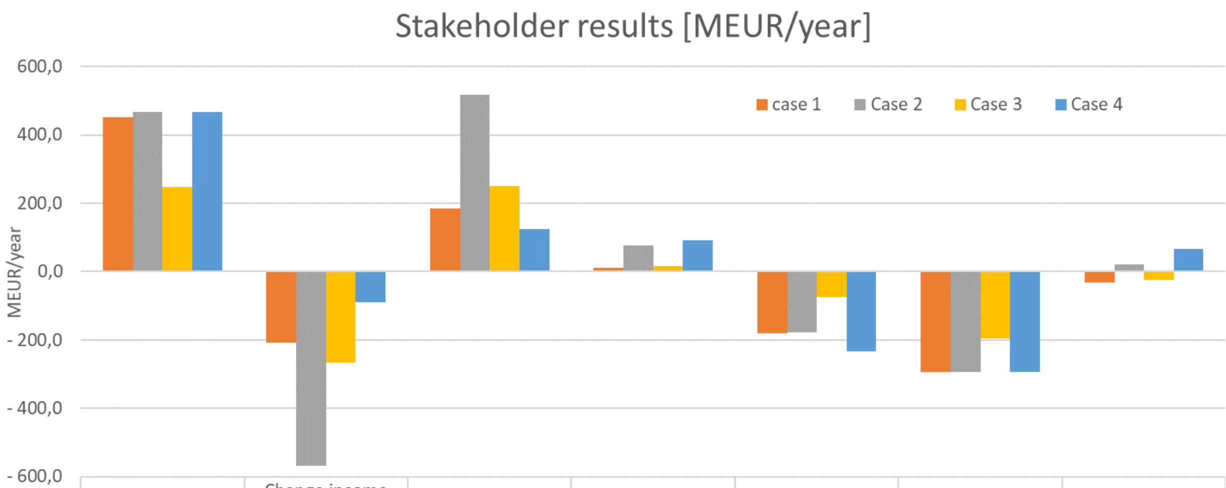
The resulting annualized investment costs for each case can be seen in Table 3. A discount rate of 5% has been assumed. The distance Sørlige Nordsjø II to Denmark and Norway is 190 and 180 km respectively (Greenstat, 2021), while the distance from Utsira Nord has been set to 20 km (Utsira Kommune, 2021). In addition to the offshore HVDC cable, it is assumed that 60 km of overhead cable will be required in all the cases.

TABLE 3: ANNUALIZED INVESTMENT COSTS IN MEUR/YEAR

	Offshore windpark	HVDC cable	HVDC nodes	Sum
Discount rate	5%	5%	5%	
Lifetime	30	40	40	
Case 1, 2	293	46	133	471
Case 3	195	6	68	269
Case 4	293	46	188	527

Effect on stakeholders and social surplus

When assessing the results and taking investment costs into account, it becomes clear that the effects of the various cases are rather different for different stakeholders in the system as well as for different regions and the total system. Figure 4 shows the results for various stakeholders in each case. From a system perspective, case 4 is the best, with case 2 in second.



	Income offshore wind farm	Change income hydropower producer	Change consumer surplus Norway	Change congestion rent Norway	Grid investment costs	Wind farm investment costs	Change social surplus Norway
case 1	451,4	- 208,4	185,2	11,9	- 179,7	- 292,7	- 32,3
Case 2	466,9	- 568,9	516,5	77,6	- 177,7	- 292,7	21,7
Case 3	247,4	- 267,0	249,0	15,4	- 74,3	- 195,2	- 24,7
Case 4	467,0	- 89,4	125,4	90,6	- 233,8	- 292,7	67,0

FIGURE 4: ANNUALIZED RESULTS FOR STAKEHOLDERS IN NORWAY IN MEUR/YEAR

From the perspective of the offshore windfarm, the revenue in case 2 and case 4 is about equally good. In both cases relying on flexible hydropower to keep the prices high despite the added energy to the system. However, the grid investment costs in case 4 are higher, so depending on who ends up paying them, wind farm investors might prefer case 2.

Seen from a Norwegian hydropower production perspective it might be best to not install the offshore wind park at all, the extra energy, which is fed into the Norwegian power system would cause a significant drop in average power price. Case 4 is the best alternative of the cases with a wind farm, but here the preference might depend on the type of the hydropower plant. Figure 2 shows that a flexible power plant is better able to take advantage of that situation. The flexibility of the power plant can be used to backup wind power production and balance the Danish power system through the additional interconnection of the offshore hub. While the hydropower plants in the areas closest to the offshore wind farm, i.e., southern Norway, are most impacted, the reduction of revenues is also significant in the north. For case 2 the revenues for hydropower in Sorland are reduced by 10%, while the revenues for hydropower in the northern areas are reduced by 7%. A consumer in Norway would stand to gain in all the cases, but still, case 2 would yield significantly lower prices than the other options and therefore higher consumer surplus.

These different perspectives show that distribution effects of installing new generation assets in the power system surrounding the North Sea can lead to not expected incentives of market stakeholders, which then will lead to not optimal decisions seen from a system perspective.

Conclusion

This paper presents an analysis of four different cases for the construction of offshore windparks in the Norwegian territory of the North Sea. The focus of the case study is on the locations "Sørlige Nordsjø II" and "Utsira Nord" as well as their connection to the power system and additional required infrastructure, such as HVDC cables.

The assessment shows that it is important to assess the distribution effects for all the cases and analyse the actual incentives for the different stakeholders in the system, which will not necessarily lead to the optimum for the social welfare. Based on the above discussion the investment for an offshore windpark cannot be recovered only based on its income, but the overall effect on social surplus is nevertheless positive for two of the cases. In case 3 the change in social surplus is not positive but because an offshore wind farm with floating turbines might help reduce costs, it could be worth building anyway.

The main conclusions of the study are:

1. The offshore windpark will receive the best economic result if it is connected to Norwegian hydropower
2. Additional power from windpower production fed into the Norwegian power system reduces average power prices and producer surplus, but can lead to an increase of total social welfare
3. In addition, through the extra power production, the energy shortage in the driest years vanishes, which also reduces the risk of involuntary load shedding.
4. To achieve the optimal design of the system, redistribution policies might be necessary to provide correct incentives for different stakeholders and the development of the system.

References

Farahmand, H., Huertas-Hernando, D., Warland, L., Korås, M., & Svendsen, H. G. (2011). Impact of system power losses on the value of an offshore grid for North Sea offshore wind. *2011 IEEE Trondheim PowerTech.* Trondheim: IEEE.

Gea-Bermúdez, J., Pade, L.-L., Juhani Koivisto, M., & Ravn, H. (2020, January 15). Optimal generation and transmission development of the North Sea region: Impact of grid architecture and planning horizon. *Energy*.

Greenstat. (2021). *Optimal utnyttelse av energi fra havvind i Sørlige Nordsjø II.* Bergen: Greenstat.

Jaehnert, S., Korpås, M., Doorman, G., & Hyldbakk, I. M. (2015). On the profit variability of power plants in a system with large-scale renewable energy sources. *12th International Conference on the European Energy Market (EEM)* (pp. 1-5). Lisbon, Portugal: IEEE.

Kristiansen, M., Korpås, M., & Farahmand, H. (2018). Economic and environmental benefits from integrated power grid infrastructure designs in the North Sea. *EERA DeepWind.* Trondheim: IOP.

Olje- og energidepartementet. (2021). *Energi til arbeid - langsiktig verdiskaping fra norske energiressurser.*

Statnett. (2021, July 2). *LMA-oppdatering.* Retrieved August 16, 2021, from https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/publiserte-rapporter-og-utredninger/

Til Kristian Vrana, P. H. (2018). Estimation of investment model cost parameters for VSC HVDC transmission infrastructure. *Electric Power Systems Research, 160*, 99-108.

Utsira Kommune. (2021). *Utsira gir energi*. Retrieved September 23, 2021, from https://www.utsira.no/utsira-nord/

Wolfgang, O., Haugstad, A., Mo, B., Gjelsvik, A., Wangensteen, I., & Doorman, G. (2009). Hydro reservoir handling in Norway before and after deregulation. *Energy*, 1642-1651.

Øvrebø, O. A., & Øystese, K. Å. (2021, August 16). *Energi og klima*. Retrieved from Energi og klima: https://energiogklima.no/nyhet/det-perfekte-stedet-for-offshore-vind-i-europa/

www.ntnu.no/ntrans

NTRANS

We study the role of the energy system in the transition to the zero-emission society.