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Growth and Economic Performance of the Norwegian Wind Power Industry and Some Aspects of the Nordic Electricity Market

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Abstract: Electricity has been produced in Norway in hydropower plants since 1877. The first wind power plant was put into operation in 1986. The growth in wind power production was weak in the first years after the turn of the millennium, but after Norway joined the Swedish subsidy scheme Tradable Green Certificates in 2012, there was significant growth in the wind power industry. While most of the hydropower production in Norway is owned by the public sector, the majority of wind power production is owned by foreign investors. Since wind power has been very much discussed in Norway, a levelized cost of energy (LCOE) model that can be well suited for this type of discussion is presented. The point here is that one must include all the costs, including the externalities. The Norwegian electricity market is dominated by a single player: Nord Pool. Ninety-six percent of all the electricity produced in Norway is sold through the power exchange Nord Pool, and the prices set by Nord Pool affect the finances of all the electricity producers in Norway, as well as producers in Scandinavia and the Baltic countries. This paper is a survey of the growth, development of production and economic performance of the Norwegian wind power industry and some aspects of the electricity market in the Nordic countries.

Keywords: wind power in Norway; the Nordic electricity market; producer's profit; LCOE

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Citation: Idsø, J. Growth and Economic Performance of the Norwegian Wind Power Industry and Some Aspects of the Nordic Electricity Market. *Energies* **2021**, *14*, 2701. https://doi.org/10.3390/en14092701

Academic Editor: Galih Bangga

Received: 22 March 2021
Accepted: 23 April 2021
Published: 8 May 2021

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1. Introduction

Electricity has been produced in Norway since 1877 [1]. For more than a hundred years, hydropower was the dominant production technology. The first wind farm was put into operation in 1986. Despite large public subsidies, few investors had the courage to invest in wind power. Wind power was expensive compared to hydropower, and the knowledge of wind power technology was limited.

With a nascent climate crisis as a justification, wind power development has been awarded subsidies and indirect financial support from the state [2]. Prior to 2012, financial support was provided by the state, covering almost 40 per cent of the investment cost. However, in 2012, Norway entered into a collaboration with Sweden in a scheme called Tradable Green Certificates (TGC) [3]. Eighty-eight percent of the installed wind power as of January 2021 has been installed after 2010 [4]. It is likely that the TGC scheme has contributed to this.

In 2020, 9.9 TWh of wind power was produced in Norway. The total installed capacity was 3977 MW distributed over 1164 wind turbines at the end of the year. Of this, 1532 MW and 5.3 TWh were completed during 2020. Wind power accounted for just over six per cent of the total power production in Norway. The average turbine size is 3.4 MW, and the capacity factor is 37.4 percent [5]. In addition, license has been granted to develop wind power with an expected production of 12 TWh. This work has only just begun [1].

The system price of electricity in the Nordic region is determined by the electricity market operator Nord Pool AS. This is a limited company with headquarters in Oslo. Nord

Pool is owned by electricity grid companies from the four Nordic countries Norway, Sweden, Finland, and Denmark. The system price varies from hour to hour and is determined by the electricity producers reporting their expected production for the next day. Based on expected production and expected consumption, Nord Pool sets a price that provides balance in the market [6]. In this paper, we first look at some of the characteristics of the Nordic electricity market. Then, we describe the development in wind power in Norway and examine the profitability of wind power investors.

While wind power development previously met little resistance, there has in recent years been a great deal of discussion about this in Norway [7]. We suggest a model that can be used in this discussion. The main point of the model is that one must not simply take into account encroachment on nature and the habitats of animals and plants, but also take into account the reduced greenhouse gas emissions that increased production of renewable energy can lead to.

While virtually all hydropower production in Norway is owned by the state municipalities or counties, three quarters of wind power production has foreign owners [2]. When foreign investors find it interesting to invest in renewable power production in Norway it is natural to investigate the profitability of these investments.

Although the profitability of individual projects has been discussed in the literature [2], no one has so far examined the profitability of the entire population of wind power projects that have been implemented in Norway.

It may be of interest to investigate whether the development of wind power in Norway, which has so far benefited from subsidies, has been economically efficient. Questions that should then be investigated are: Does subsidized development of wind power lead to the most efficient use of society’s resources? In such a further analysis, the profitability of the companies that have carried out the development is a necessary part

In general, companies’ future prospects depend on the market situation. For that reason, we have also examined the Norwegian market for electricity.

2. Data and Method

In Norway, there is a public register that everyone has access to (Brønnøysundregistrene [8]). This register contains all the financial accounts of all the limited companies for the last ten years. Since all financial information about all companies is available, we have used this information in our survey. Our survey is therefore not a sample survey but a survey of the entire population.

In addition to information from Brønnøysundregistrene, information from Nord Pool was used [6]. Nord Pool publishes the electricity prices for each hour in each price area as well as the system price. The system price is a theoretical price, which is calculated on the assumption that there are no transmission restrictions (bottlenecks) in the Nordic transmission network. The system price is common to the entire Nordic market and serves as a reference price for pricing the financial power trade in the Nordic region. Nord Pool also calculates the system price for power in the next 24 h. For our survey, we downloaded all relevant price and consumption information from Nord Pool. From Nord Pool, we obtained price and consumption information for every hour from 0000 on 1 January 2013 to 2400 on 31 December 2020 from Norway, Sweden, Denmark, and Finland. In the case of Norway, this includes 96 per cent of all electricity used in the country. That means the sales figures are a good indicator of the consumption.

When it comes to sales figures for the other Nordic countries, these are lower than the consumption. This is because it is possible to buy electricity from players other than Nord Pool in these countries. However, while the figures from Nord Pool do not include all consumers of electricity in the other Nordic countries, we can use the figures to uncover the consumption pattern in all Nordic countries. From Nord Pool, we took time series consisting of sales volume and price of electricity. In total, we based our research on 70,136 observations—one observation for each hour throughout the period of 2013–2020.

3. Fluctuations of Consumption in the Nordic Energy Market

Needs represent a fundamental driver of the fluctuations in the Nordic electricity market. Needs determine the consumption and thus the production and the imports. A study of the Nordic electricity market revealed three cycles that appear through the following oscillations:

1. Annual fluctuations with the highest consumption in January and the lowest in July.
2. Weekly fluctuations with the highest consumption in the middle of the week and the lowest on Sundays.
3. Daily fluctuations with the lowest consumption between three and four in the morning and maximum of one hour before noon.

The cause of fluctuations in consumption is found in natural conditions such as cold winters, economic conditions, and cultural conditions. The absolute value of the correlation coefficient between temperature and consumption of electricity in Norway is 0.8. As discussed later (page 11), most of the annual fluctuations in consumption can be explained by changes in temperature. The cultural feature that is important is that society is designed so that most people sleep at the same time. Thus, human activities will also vary according to the sleeping pattern, and we can expect that the energy requirement will also vary in a similar way. For energy producers, knowledge of fluctuations in the market will have economic value when maintenance is to be planned.

3.1. The Annual Fluctuations in Consumption

The annual average consumption in Norway in the period of 2013–2020 was 131 TWh. The highest and lowest consumptions in this period were 135 TWh and 126 TWh, respectively. As shown in Figure 1 and Table 1 there is a certain pattern in the annual consumption. January—which is normally the coldest month—has the highest consumption, while the summer and holiday month of July has the lowest consumption. This pattern is the same for all the Nordic countries. However, the difference is that Sweden, Denmark, and Finland do not deviate as much from January consumption as Norway. While Norway's July consumption was 56 per cent of January consumption, the corresponding figure was 65 per cent for the other Nordic countries. This is shown in Figure 1b.

(**a**) Numbers in MWh. (**b**) Relative numbers.

Figure 1. The average consumption per hour in the different months in all Nordic countries measured in MWh (**a**) and measured as the percentage of consumption in January (**b**).

Since much of the electricity is used for heating, there is a strong correlation between electricity consumption and temperature. The correlation coefficient between consumption and temperature in Norway was minus 0.80 in the period of 2013–2020. Data basis: 70,128 observations, significantly at the 0.01 level.

Table 2 shows that consumption in July is lowest both in Norway and in the other Nordic countries. However, the relative difference between January consumption and July consumption is greater in Norway than in the other Nordic countries.

Table 1. Average consumption to Nord Pool's customers measured in MWh per hour in all months of the year in the years 2013–2020 in the four Nordic countries.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Sweden	19,736	19,259	17,970	15,524	13,601	12,720
Finland	11,463	11,033	10,562	9367	8295	7820
Denmark	4261	4202	4018	3634	3518	3519
Norway	19,304	18,671	17,605	15,067	12,649	11,308
Month	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Sweden	11,717	12,510	13,499	15,158	17,101	17,967
Finland	7884	8159	8542	9446	10,127	10,347
Denmark	3337	3532	3603	3788	4040	4044
Norway	10,701	11,048	12,268	14,026	16,318	16,805

Table 2. The average consumption compared with the consumption in January in Sweden, Denmark, Finland (S, D, F), and Norway (Nor) in the period of 2013–2020. Consumption in January is equal to 100.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
S, D, F	100	97	92	80	72	68	65	68	72	80	88	91
Nor.	100	97	91	78	68	62	59	61	66	77	89	94

Market fluctuations mean risk for market participants, and the standard deviation is often used as a measure of risk. A study of the standard deviation of the monthly consumption in all Nordic countries indicates the following:

1. The standard deviation of the consumption (s_i) and the consumption (c_i) are proportional.
2. The standard deviation is different for each country i. This means that we can set

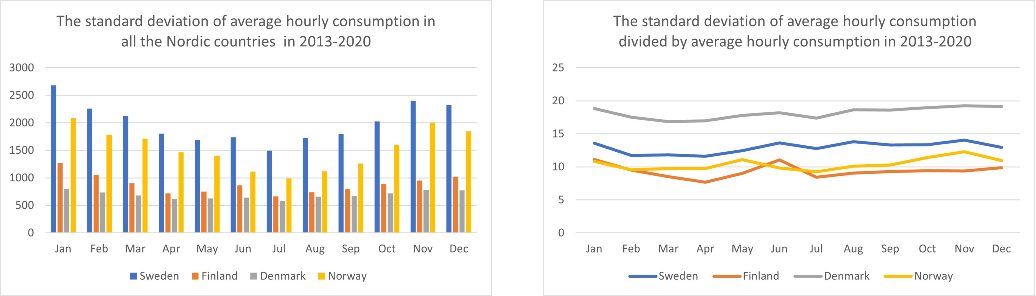
$$s_i = \alpha_i \cdot c_i \tag{1}$$

where α_i is the proportionality factor of country i.

The result is shown in Figure 2b and Table 3. Above, we used the word indicates. The reason is that we only studied the Nordic countries for a period of 8 years. We can therefore not say whether the result applies in general, and we did not find complementary scientific research in this field.

Table 3. The standard deviation of average hourly consumption divided by average hourly consumption. Figures in percent.

-	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Sweden	13.6	11.7	11.8	11.6	12.4	13.6
Finland	11.1	9.5	8.5	7.7	9.0	11.1
Denmark	18.8	17.5	16.9	17.0	17.8	18.2
Norway	10.8	9.6	9.7	9.7	11.1	9.9
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Sweden	12.8	13.8	13.3	13.4	14.0	12.9
Finland	8.4	9.0	9.3	9.4	9.4	9.9
Denmark	17.4	18.6	18.6	19.0	19.2	19.2
Norway	9.3	10.1	10.3	11.4	12.3	11.0

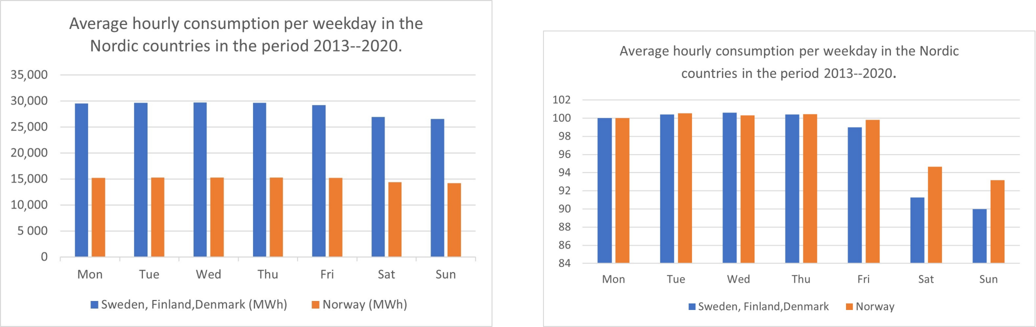


(**a**) Numbers in MWh. (**b**) Relative numbers.

Figure 2. The standard deviation of the average hourly consumption in all the Nordic countries in 2013–2020 (**a**) and the standard deviation of average hourly consumption divided by average hourly consumption in 2013–2020 (**b**).

3.2. The Fluctuations over the Week

The average consumption during a week is shown in Figure 3 and in Table 4. The consumption is roughly the same and the highest on Tuesday, Wednesday, and Thursday and the lowest on Saturdays and Sundays. We observed the same pattern regardless of the time of year.



(**a**) Numbers in MWh. (**b**) Relative numbers.

Figure 3. Average consumption per hour by day in absolute numbers (**a**) and compared to Monday (**b**) in the years 2013–2020 in the Nordic countries. Monday consumption is equal to 100.

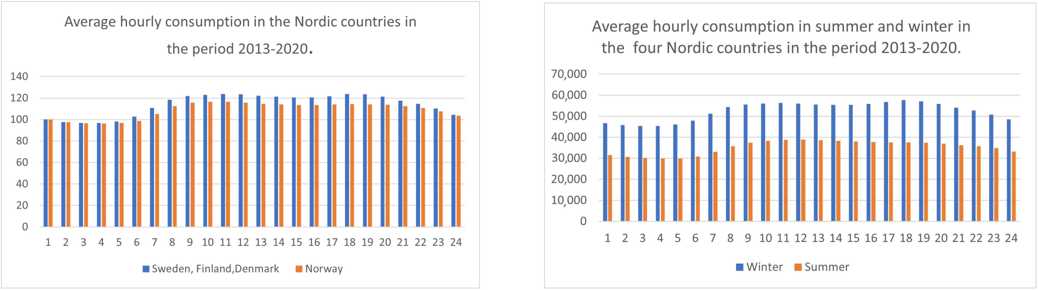
Table 4. The relative and absolute hourly consumption during the week in Norway and the other Nordic countries (sum of consumption in Sweden, Finland, and Denmark) in the period of 2013–2020.

-	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Other Nordic (%)	100.0	100.4	100.6	100.4	99.0	91.3	90.0
Norway (%)	100.0	100.5	100.3	100.4	99.8	94.6	93.2
Other Nordic (MWh)	29,520	29,642	29,701	29,639	29,220	26,937	26,563
Norway (MWh)	15,207	15,290	15,252	15,275	15,178	14,392	14,169

3.3. The Daily Fluctuations

Consumption over the course of a day also follows a pattern that seems to be more or less the same in all the Nordic countries. Figure 4a shows the relative consumption over the day for Norway and the other Nordic countries. The pattern is the same in the summer (June, July, August) and winter (December, January, February); only the level of consumption is different. This is shown in Figure 4b.

Table 5 shows the average consumption per hour in Norway and in the other Nordic countries (Sweden, Finland and Denmark) in the period 2013–2020. All figures are as a percentage of the average consumption between midnight and 0100.



(**a**) Norway and other Nordic countries.

(**b**) Winter and summer consumption.

Figure 4. In figure (**a**), average consumption per hour during the day in Norway and the other Nordic countries compared to consumption between midnight and 0100 in the years 2013–2020 in these countries is shown. Figure (**b**) shows the relative consumption in summer and in winter.

Table 5. Average hourly consumption in Norway and the other Nordic countries (Sweden, Finland, and Denmark) in the period of 2013–2020. All figures are seen in relation to consumption from midnight to 0100.

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Other Nordic countries	100.0	97.7	96.8	96.8	98.1	102.8	110.9	118.5
Norway	100.0	97.7	96.5	96.3	96.8	98.8	105.0	112.6
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Other Nordic countries	121.8	123.0	123.8	123.5	122.3	121.3	120.6	120.6
Norway	115.7	116.4	116.6	115.8	114.7	114.0	113.6	113.6
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Other Nordic countries	121.5	123.8	123.6	121.4	117.5	114.7	110.2	104.4
Norway	114.2	114.3	114.1	113.7	112.5	110.7	107.7	103.6

4. Some Aspects of the Nordic Electricity Market

The electricity market is subject to a fundamental condition. At any time t in all price areas i, the following condition must be met:

$$\underbrace{a_t^i + c_t^i}_{\text{demand}} \leq \underbrace{x_t^i + z_t^i + b_t^i}_{\text{supply capacity}} \tag{2}$$

where all the variables are measured in for instance MW and c_t^i is the consumption at time t in area i, a_t^i is the export at time t from area i, x_t^i is the production capacity at time t in area i, z_t^i is the import capacity at time t to area i, and b_t^i is backup production facilities.

As can be seen from Equation (2), the left side represents the demand, while the right side represents the production side. Above, we have shown how demand varies during the year, week, and day. However, when the production is partly nature-based and cannot be regulated, such as in the case of wind power, the production capacity will also vary. In other words, both the right side and the left side of Equation (2) will vary. This can create certain challenges.

4.1. The Art of Balancing the Market

In the Nordic countries, a large part of electricity production is based on hydropower and wind power. For instance, in 2019, 93.4 per cent of the consumed electricity in Norway was produced in hydropower plants, while 4.1 per cent was produced in wind power plants [9].

The condition given in Equation (2) is absolutely binding. A special challenge with a system that is almost exclusively based on hydropower and wind power is that natural conditions can reduce production capacity in a short time, while it normally takes years to increase the production capacity. The production capacity of hydropower and wind power varies for the following reasons:

1. Drought. The water reservoirs have little water.
2. Cold weather. The smaller rivers are frozen. The small power plants do not produce.
3. In the winter, there is less water flow in the rivers. River power plants that do not have reservoirs produce less.
4. It may blow too little or too much. The result is reduced production of wind power.

If the desired consumption exceeds the total ordinary production and import capacity, the following options are available for the network operator:

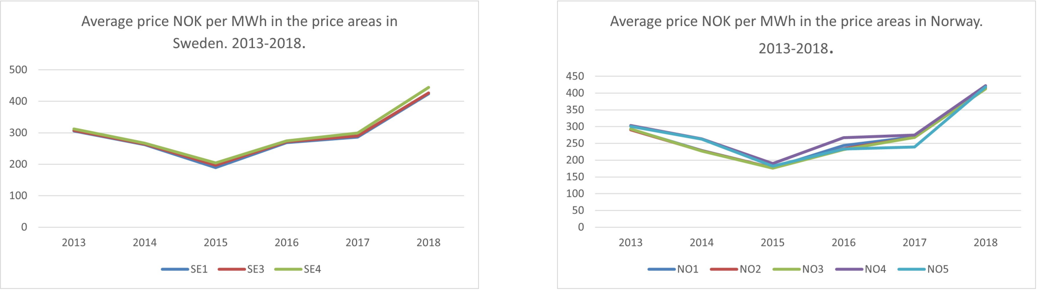
1. Increase production using the backup system.
2. Encourage customers to reduce the desired consumption.
3. Set the price so high that the desired consumption is reduced. A prerequisite for this to be effective is that a sufficiently large share of the electricity is sold on the spot market. If most of the electricity is sold at fixed price contracts, this possibility does not exist.
4. Pay large customers to reduce consumption.
5. Disconnect some of the customers.

The limitation that lies in Equation (2) can—when consumption approaches the capacity limit—lead to extreme fluctuations in the price of electricity. An example: On 12 March 2021 between 8 a.m. and 9 a.m., 1 MWh cost EUR 249.98 in Oslo. Three hours later, the price was EUR 50.17 per MWh [10].

In the following, we examine the price development and fluctuations in electricity prices in the Nordic market. We focus on normal situations, but one should be aware that extreme situations can occur, and there are various reasons why situations can occur.

Different price areas have different production capacities and different import capacities. To be able to control the supply system so that Equation (2) at any time is satisfied, electricity is—if necessary—priced differently in different areas.

The Nordic countries are divided into the following price areas: Norway has 5 price areas, Sweden has 4, Denmark has 2, while Finland has one. Usually, there is little difference between the prices in the different areas (see Figure 5). If there are differences in price between price areas, these are quickly leveled. Electricity always flows where the price is highest.



(**a**) Sweden. (**b**) Norway.

Figure 5. The average price in NOK per MWh in the price areas in Sweden and in Norway in the years 2013–2018.

4.2. Electricity Prices in the Nordic Countries since 2013

4.2.1. Development in the Average Price

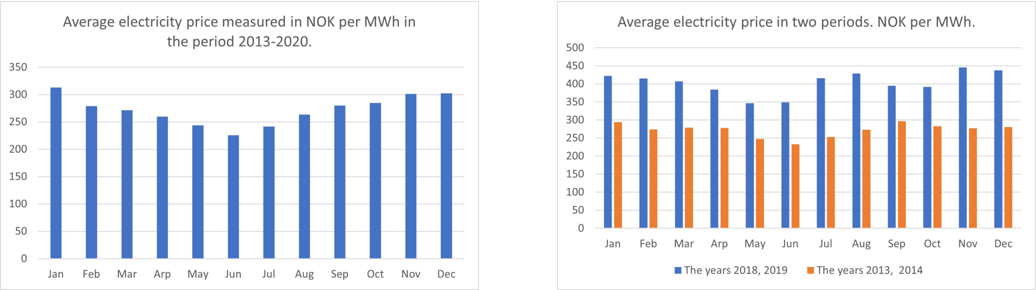
Based on the average prices for the individual years (see Table 6), we cannot conclude that electricity prices have risen during this period.

Table 6. Average system price in the Nordic electricity market (NOK per MWh). Maximum, minimum, and standard deviation in the period of 2013–2020.

Year	2013	2014	2015	2016	2017	2018	2019	2020
Av. price	296.63	247.7	187.11	249.66	274.33	422.55	383.5	115.64
Maximum	818.5	618.03	645.86	1937.91	1239.31	1908.34	863.32	542.08
Minimum	11	16.7	10.37	69.62	47.53	20.52	22.63	−10.35
Std. Dev.	49.77	45.99	69.67	83	49.08	96.34	79.32	84.86

4.2.2. Annual Fluctuations in Electricity Prices

In Table 7 and Figure 6, we note that June has the lowest price. In the years 2019–2020, the price in June was 78 per cent of the price in January, while the corresponding figure was 72 per cent for the entire period of 2013–2020. It is difficult to know whether this is due to changes in social conditions or whether it is due to climatic conditions.



(**a**) The years 2013–2020. (**b**) The years 2013–2014 and 2018–2019.

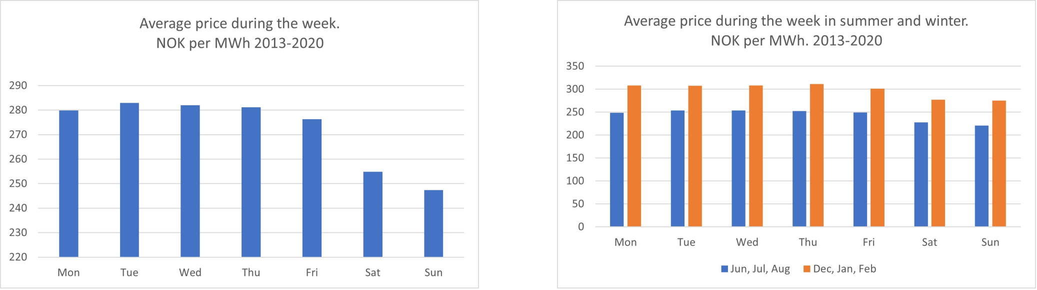
Figure 6. Average electricity price in the period of 2013–2020 and in the periods 2018–2019 and 2013–2014. NOK per MWh.

Table 7. Average monthly prices measured in NOK per MWh in the Nordic electricity market for the years 2019–2020 and for the years 2013–2020.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
The years 2019–2020	323.6	300.1	296.1	288.0	265.4	252.9	272.5	287.8	295.9	302.5	334.3	314.9
The years 2019–2020	100%	93%	91%	89%	82%	78%	84%	89%	91%	93%	103%	97%
The years 2013–2020	313.0	278.6	271.7	259.5	243.8	225.5	241.5	263.4	279.9	284.7	301.0	302.2
The years 2013–2020	100%	89%	87%	83%	78%	72%	77%	84%	89%	91%	96%	97%

4.2.3. Weekly Fluctuations in Electricity Prices

The economic activity and behavior of the population affect the consumption of electricity. This affects the electricity market and thus also the price of electricity. We see this in Figure 7a,b. Figure 7a shows the average price per MWh measured in NOK in the period 2013–2020 over the entire year. Figure 7b shows the average price per MWh measured in NOK in the period 2013–2020 in the summer months (June, July and August) and in the winter months (December, January and February).

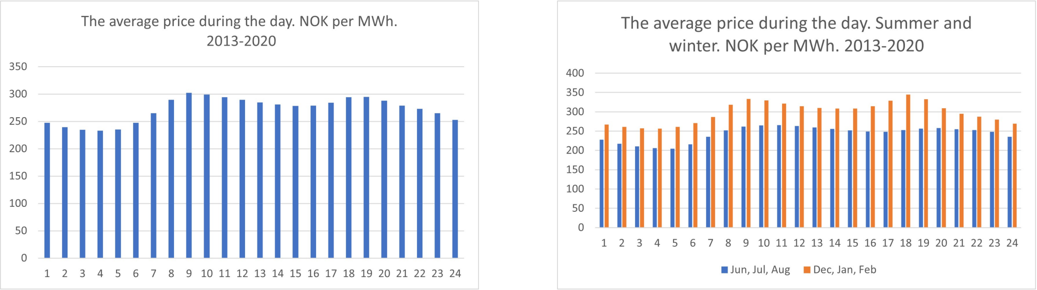


(**a**) The years 2013–2020. (**b**) The years 2013–2020, summer and winter.

Figure 7. Average price per MWh measured in NOK in the period 2013–2020 over the entire year (**a**) and average price per MWh measured in NOK in the period 2013–2020 in the summer months (June, July and August) and in the winter months (December, January and February) (**b**).

4.2.4. Daily Fluctuations in Electricity Prices

In addition to weekly fluctuations in electricity prices, the price fluctuates during the day. A survey of prices in all days from 1 January 2013 to 31 December 2020 shows that the daily fluctuation has its maximum point at approximately 0900 in the morning, but there is also a local maximum point at 1900. This is shown in Figure 8a. Figure 8b shows that the daily maximum point is not stable over the year. In winter, the daily maximum point is at 1800 in the evening while it is in the morning in the summer.



(**a**) The years 2013–2020. (**b**) The years 2013–2020, summer and winter.

Figure 8. Average electricity price during the day (**a**) in the period of 2013–2020 and in the summer (June, July and August) and in the winter (December, January, February) in the period of 2013–2020 (**b**). NOK per MWh.

4.3. The Price of Electricity Produced by Wind Power

As we have observed, the price of electricity varies over the year, over the week, and over the day, and the production varies over the year. What price do wind power producers achieve for the electricity they produce? Is the average price different from the average system price? The answer to these questions depends on how wind power production is distributed over the year. Figure 9 shows the wind power production in relation to the production in January.

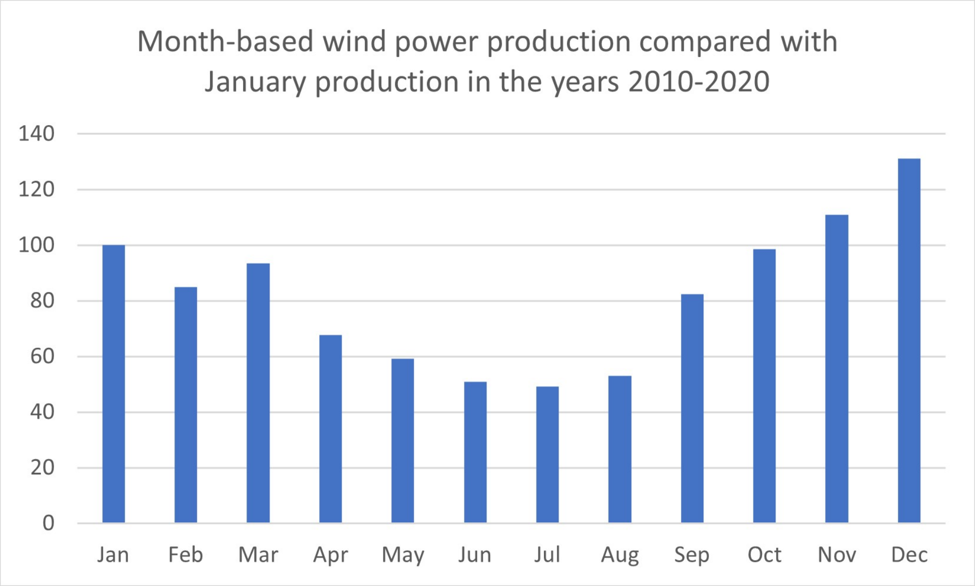


Figure 9. Monthly wind power production in Norway from January 2010 to January 2021. Based on figures from Statistics Norway.

Since the price is set for each hour, the income a power producer gains in the Nordic market if he is selling in the spot market is (R):

$$R = \sum_{t=1}^{n} p_t \cdot x_t \tag{3}$$

where t is equal to the hour number of the year from the first of January to the last hour of December. The variable n is the number of hours in the year—that is, 8760—while x_t is the production in hours t, and p_t is the system price. From Equation (3), it follows

$$p_w = \sum_{t=1}^{n} p_t \cdot v_t \tag{4}$$

where p_w is the expected price that the wind power producer achieves, v_t is the expected share of production in hours t, and p_t is the system price. Now, we do not have the production of the wind turbines for every hour; we only have the production for every month. Using the monthly production as weights, we found that wind power producers can expect a price that is 2.5 percent higher than the average system price over the year.

5. Some Aspect of the Norwegian Electricity Market

The biggest difference in the Norwegian electricity market and the market in other countries is that the consumption of electricity per person in Norway is far higher than in other countries in Europe. Table 8 shows the electricity consumption in households in Norway and The European Union and some selected countries in Europe in 2019. There is a remarkably large difference in consumption in Norway and the other countries.

Table 8. Consumption in households of electricity per capita in Norway, EU and some other countries (kWh, 2019). Source: Eurostat.

Country	Consumption in Households per Capita (kWh, 2019)
Norway	7529
Sweden	4287
Finland	4086
France	2377
Denmark	1763
Ireland	1658
European Union	1581
United Kingdom	1558
Spain	1555
Germany	1524
Italy	1096

Above we have seen that both the price of electricity and the consumption of electricity has regular fluctuations throughout the year, week and day. This is not special for Norway. All Nordic countries follow the same pattern, although the size of the fluctuations varies somewhat from country to country. But Norway differs from the other Nordic countries in that production is almost exclusively based on hydropower. This means that the production capacity that depends on the amount of precipitation will vary. In years with little rainfall, Norway is dependent on imports. This is especially true in winter when the need for heating is great. This affects the price of electricity.

If we let consumption be the dependent variable while the price, the temperature and a variable for the imported quantity are the independent variables one can set up the following equation:

$$Y_i = \beta_0 + \beta_1 \cdot P_i + \beta_2 \cdot T_i + \beta_3 \cdot \text{Import}_i + \epsilon_i \tag{5}$$

where
Y_i is the consumption in hour i in Norway.
P_i is the average price in the five areas in Norway in hour i.
T_i is the average of the temperature in the five areas in Norway in hour i.
Import_i are net import in hour i.
ϵ_i is a stochastic error.

The results from this regression analysis (Table 9) show that consumption is largely controlled by temperature.

Table 9. Estimates of R^2, β_1, β_2 and β_3.

Variabel	Result	Sig
R^2	0.725	
Price (β_1)	0.136	0
Temperature (β_2)	−0.849	0
Import (β_3), dummy	−0.236	0

From Table 9 we see that there is a positive correlation between price and quantity. This requires a more detailed explanation. Figure 10 shows the market situation for electricity in summer and in winter. The curve d_s is the demand function in summer. When it gets colder, the demand function gets a positive shift as illustrated here d_w which represents the demand function in winter. In market equilibrium in the summer the consumed quantity is Q_s while the market equilibrium in winter is Q_w. With a rising supply curve, the result will be both a higher price and a higher quantity sold as shown in Figure 10.

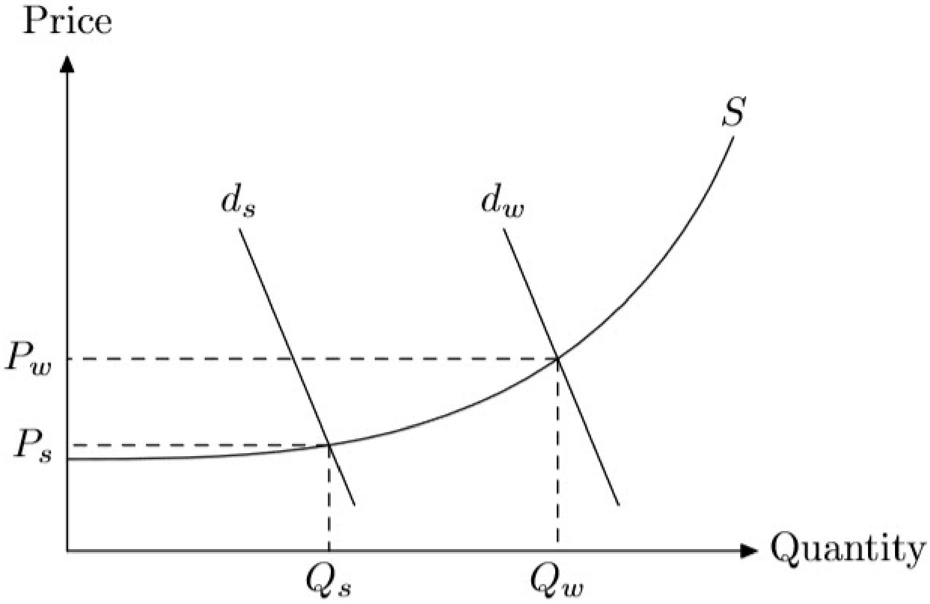


Figure 10. The demand for electricity summer (d_s) and winter (d_w).

About 90 percent of the electricity used in Norway comes from hydropower (according to Statistics Norway: 93.6 percent i 2019). The high proportion of hydropower affects the supply function. The supply curve will vary from year to year depending on how much water there is in the reservoirs in the autumn. The reservoirs do not receive supply during the winter since practically all precipitation comes as snow. This means that the producers reduce production in such a way that they have enough water in the reservoirs to produce all winter. With limited import capacity (see Table 10), Norway cannot fully rely on electricity imports.

Table 10. Cables from Norway to nearby countries. Capacity in MW.

Country	Number of Cables	Capacity (MW)
Sweden	9	3600
Denmark	4	1700
Finland	1	120
Russia	1	50
The Netherlands	1	700
Germany	1	1400
	Total	7570

In addition to this, winter capacity has also been reduced because the river power plants (power plants that do not have reservoirs) have lower production capacity due to less water in the rivers. The small power plants also do not produce anything in the winter. The reason is that the small rivers are frozen.

When production in Norway is lower than consumption, the correlation coefficient between the price of electricity and imported quantity is 0.181 (significant at 0.01 level). In the period 2013–2020, Norway was a net importer of electricity for 18,698 h out of a total of 70,128 h. This means that Norway was a net importer for 26.7 per cent of the time. 72.5 per cent of the hours of import were in the winter months of December, January and February. High imports in the winter contribute to raising the price of electricity in Norway in the winter.

6. Development of Wind Power in Norway

In 2005, only 0.57% of the world's electricity consumption was covered by wind power. In 2018, the share rose to 4.76%, and in 2020, about 12 percent of Europe's electricity consumption was covered by wind power [11]. Wind power production in Norway has had a similar development, but growth has been somewhat lower than in the rest of Europe.

Figure 11 shows the development in wind power production in Norway from January 2010 to January 2021. The large increase in wind power production in Norway started in 2017.

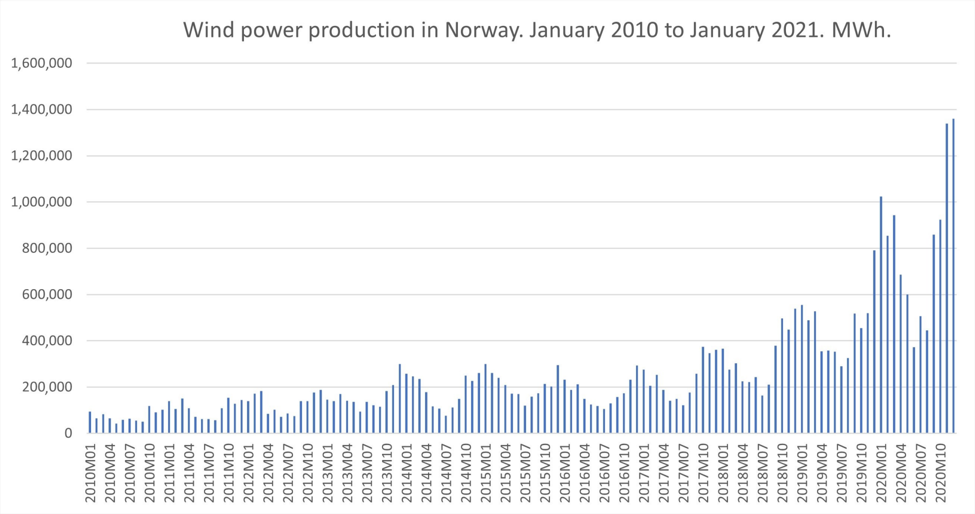


Figure 11. Monthly wind power production in Norway from January 2010 to January 2021. Based on figures from Statistics Norway.

There are two main reasons for the sharp increase in wind power production:

1. Direct and indirect subsidies from the public sector.
2. Reduction in turbine costs.

To date, there have been significantly lower costs for onshore wind power than offshore wind power production. For this reason, most of the development has taken place on land. The share of wind power production that was land-based in the Nordic countries in 2018 is given in Table 11. As the table shows, there was no offshore wind power production in Norway in 2018. The reason is that the bottom conditions off the Norwegian coast make the development of wind power complicated and expensive, but the government has proposed opening two areas in the North Sea for the construction of offshore wind [12].

Table 11. The share of wind power production that was land-based in the Nordic countries in 2018.

Country	Sweden	Denmark	Finland	Norway
Share of production onshore (%)	96	97	98	100

With good access to cheap hydropower and an average annual export surplus of electricity of 6761 GWh [13] in the period of 2003–2019, Norway has not had good enough incentives for the development of wind power. However, this has changed in recent years. The reason is an adopted policy that aims to reduce all emissions of greenhouse gases [14]. Even though Norway in normal years produces more energy than the country consumes, this will probably change in a few years, the reason being the following projects [15]:

1. Change in the production process at the ammonia factory at Herøya. This will happen before 2027. Expected consumption is 4–6 TWh.
2. The company Freyr is building a battery factory in Mo i Rana. Full production from 2025. Expected consumption is 2.5 TWh.

3. The company Morrow Batteries is building a battery factory in Agder. Expected consumption is 2.5 TWh.
4. Electrification of oil production in the North Sea. Expected consumption 10–17 TWh.

Even though there are plans, the situation is that as of March 2021, no final decision has been made on all these projects. It is therefore uncertain how much the energy demand will increase.

Figure 12 shows the development in wind power production in the four Nordic countries in the period 2005-2020. Sweden is the country that has had the largest increase in production.

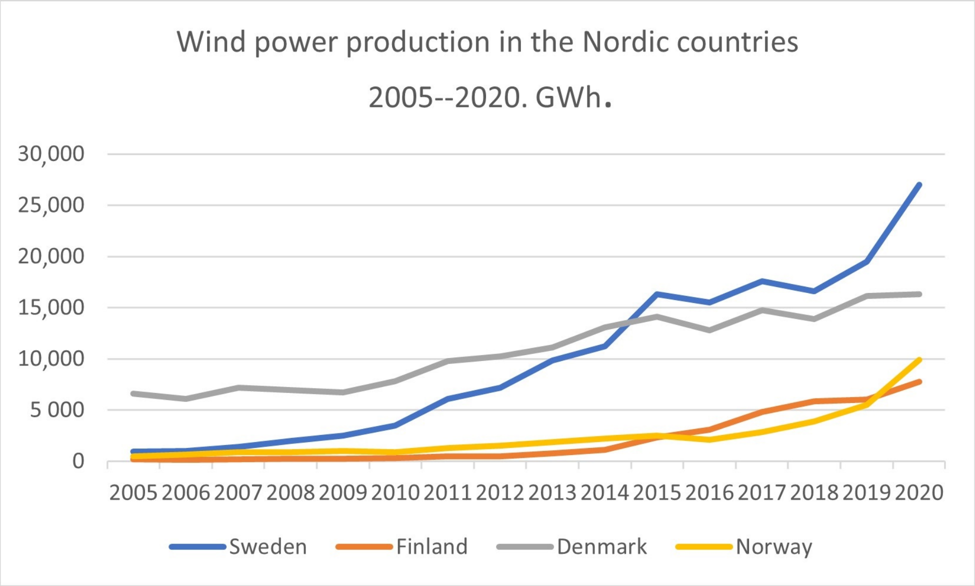


Figure 12. The wind power production in the four Nordic countries in 2005–2020. Measured in GWh.

The significance of wind power production for the electricity supply in a country is best seen if the wind power's share of the total electricity production in the country is calculated. The result of this is shown in Table 12. From the table we see that Norway is the country with the lowest share of wind power production.

Table 12. Total wind power production in the Nordic countries in the years 2005–2019. Percent of total electricity production in the country.

Country	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Sweden	0.6	0.7	1.0	1.3	1.8	2.3	4.1	4.3
Finland	0.2	0.2	0.2	0.3	0.4	0.4	0.7	0.7
Denmark	18.2	13.4	18.2	18.9	18.5	20.1	27.7	33.5
Norway	0.4	0.5	0.7	0.6	0.7	0.7	1.0	1.0
Country	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Sweden	6.4	7.3	10.1	9.9	10.7	10.2	11.8	-
Finland	1.1	1.6	3.4	4.5	7.1	8.3	8.7	-
Denmark	32.0	40.6	48.8	41.9	47.6	45.8	55.2	-
Norway	1.4	1.6	1.7	1.4	1.9	2.6	4.1	6.4

The Norwegian Water Resources and Energy Directorate (NVE) carried out an analysis and predicted the growth in electricity production until the year 2040 [16]. The main conclusion of this study is shown in Table 13. The NVE expects that net power production will increase by almost 100 TWh in the period of 2020–2040 and that the largest increase will come from increased wind power production. Since fossil power production and nuclear power are to be phased out, other power production must have strong growth.

Table 13. Total electricity production in the Nordic countries in the year 2019 and expected production in the year 2040. Figures in TWh. Figures from The Norwegian Water Resources and Energy Directorate.

	Hydro	Wind	Nuclear	Bio	Sun	Other
Production in 2019	219	53	78	22	1	48
Percentage change	6	205	−41	41	1624	−50
Production in 2040	232	161	46	31	21	24

6.1. The Wind Power Producers

While more than 90 per cent of hydropower production is owned by the state, counties or municipalities, more than two thirds of wind power production has foreign owners. Companies that produce wind power as their main activity are registered under NACE code 35112. In addition to these, there are some hydropower producers who have some wind power production in addition to hydropower production. In our survey, we focused on those registered under NACE code 35112.

As can be observed from Tables 14 and 15, the financial result for most wind power companies was weak in the period of 2010–2019. One explanation may be that wind power production is a new industry in Norway and it takes time to create profitable operations. The average age of wind power companies is between seven and eight years in the whole period.

As can be seen from Figure 13, the investments in wind power production have grown strongly since 2015. The value of fixed assets in 2019 was almost NOK 30 billion.

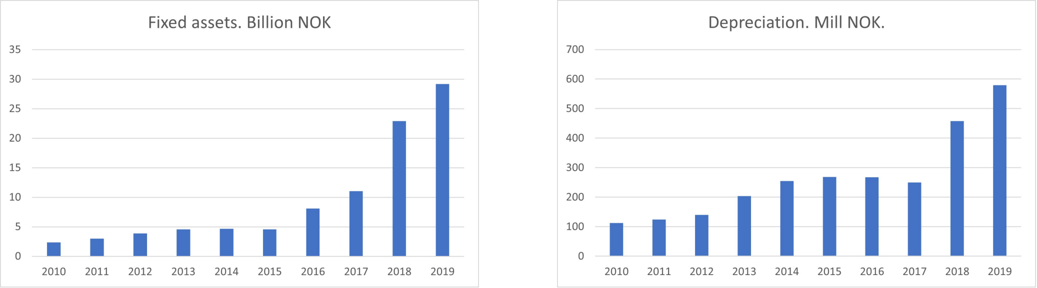
Table 14. The total number of companies that have wind power production as their main activity and the percentage of companies with negative EBIT (Earnings before interest and taxes).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Companies	55	61	64	69	71	76	82	88	105	112
EBIT ≤ 0, (%)	91	85	92	86	83	83	83	75	69	73

Although there have been large investments, this has not created many new jobs. As we see from Table 15, the total wage costs in the entire industry were only NOK 14 million in 2019.

Table 15. The sum of all companies' EBIT and average EBIT. The sum of the annual profit after tax and the sum of the wage costs. Numbers in NOK Mill.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
EBIT (sum)	38	104	48	63	91	71	141	336	704	520
EBIT (mean)	8	12	10	6	8	5	10	15	21	17
Annual result	24	64	3	29	21	17	74	162	452	331
Labor cost	0	1	1	4	21	6	11	6	9	14



(**a**) Fixed assets. (**b**) Depreciation.

Figure 13. Book values of fixed assets to all wind power producers in Norway and the depreciation. Period of 2010–2019.

6.2. LCOE, Market Price and Fiancial Support

For wind power production to be profitable for investors, the market price of electricity plus financial support from the authorities must be higher than the costs that are charged to the business. Worldwide, many renewable electricity projects are granted production support to increase the likelihood that the projects will be profitable for investors. This is also the case in Norway and Sweden. Since 2012, Norway and Sweden have collaborated on a scheme to award producers of renewable energy with so-called green certificates [17–19].

As shown in Table 16, the market price—and thus the financial support to the energy producers—has been very variable in the period of 2012–2020. The highest price was 19 cents per kWh, and the lowest price was 4 cents per kWh.

Table 16. The average market price of green certificates in the period of 2012–2020, cents of NOK per kWh produced power.

Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Cert.price	15	19	18	16	14	8	14	9	4

6.3. The Fosen Development

The Fosen development is the largest wind power project implemented in Europe and contributed to Norway being the country with the largest development of wind power in Europe in 2020 [20]. The development of the project started in 2016. The first production started in 2017, and in 2020, full production was achieved. The project has a total capacity of 1057 MW, and the expected annual production is 3.6 TWh. The Fosen development has been carried out by the Norwegian state-owned company Statkraft as operator on behalf of Fosen Vind DA, in which Statkraft is the largest owner with 52.1 percent.

In the Fosen development, wind power production will be located in remote mountain areas to reduce the negative externalities. Figure 14 is a picture from this project. In the Fosen project, 277 wind turbines were installed. The turbine manufacturer was Vestas, and the following turbine types were used: Vestas V117-3.6 MW, Vestas V117-4.2 MW and Vestas V136 4.2 MW. A total of 1057 MW in six wind farms was installed. The technological development during the construction period meant that the turbine types were changed from 3.6 to 4.2 MW during the development. The total investment is budgeted at NOK 11 billion, where almost 3 billion NOK has been invested by local companies. In the construction process, local companies have largely been used when it comes to road construction, erection sites, and turbine foundations, as well as service and operating buildings. The duration of the license is 25 years, which is also the estimated life of the turbines. More than 2500 special transports were carried out in three assembly seasons from three different ports. Internal roads with up to 18% incline were used.

Figure 14. From the Fosen development. Wind power production is located in remote mountain areas.

Norway is the country that has invested the least in wind power of the Nordic countries, but the Fosen development led Norway to the top in increased installed capacity in wind power in the year 2020. This is shown in Table 17.

Table 17. Due to the Fosen project, Norway topped the list of countries with the largest wind power development in Europe in 2020.

Country	GW
Norway	1532
Germany	1431
Spain	1400
France	1318
Turkey	1224
Sweden	1007
Poland	858

7. Costs and Wind Power

Levelized cost of energy (LCOE) is the usual way of stating the costs associated with the development of energy. The economist Anders Skonhoft proposes a cost model that deviates from the conventional method of calculation [2]. Skonhoft's model is more realistic since his model also takes into account the interventions in nature. Skonhoft also uses continuous time in contrast to the conventional calculation method where one usually uses discrete time [21,22]. The advantage of using continuous time is that the mathematical expressions become simpler and—if that means anything—more elegant.

Skonhoft's model is based on the thoughts of John Krutilla in his famous article in the American Economic Review from 1967 [23]. Krutilla pointed out that untouched nature has an alternative cost, and this type of cost can be very important when the intervention in nature is irreversible. Krutilla argued here that pristine natural resources have a value in themselves ('intrinsic value'), and that people are thus willing to pay to take care of such a resource, even if they have never seen or experienced the area. An option value was also included. The option value is lost if the intervention is irreversible. The issue that Krutilla raised has received a great deal of attention in the field of development of renewable energy; see, for example [24,25].

We expand the model to Skonhoft with three new elements. In the expansion, we include the cost of connecting the wind farm to the grid, the costs of investing in a backup solution, and cost savings as a result of reduced greenhouse gas emissions. The advantage of Skonhoft's model compared to the conventional LCOE models is that it splits the total costs into several elements. This makes it easier to use it as a basis for discussions. Our model thus consists of the following seven elements:

1. The capital costs associated with turbine investments.
2. The capital costs associated with capital investments, such as roads and cables.
3. The cost of connecting the wind farm to the grid.
4. Operating costs.
5. Investments in backup solutions.
6. The environmental costs.
7. The development of wind power can lead to less emissions of greenhouse gases. It can reduce climate change and lead to lower costs for society. This cost reduction must be included in the calculations.

All Costs Spread over All Years

We assume that the wind farm has a lifespan of T years. When the service life is over, reinvestments are made. The project thus has an infinite lifespan. Furthermore, it is assumed that the cost of capital (calculation rate) is equal to r. Total turbine capacity is equal to Y. Investment cost per unit turbine capacity at time $t = 0$ is equal to c. Thus, the investment at time $t = 0$ is equal to cY. Therefore, present value of the total investments is

$$N_0 = cY + cYe^{-rT} + cYe^{-r2T} + \cdots + cYe^{-r\cdot\infty} \tag{6}$$

If we assume technological improvements, then these can be included as a reduced cost per unit of turbine capacity. This means that the reduced cost over time t becomes equal to $ce^{-\alpha t}$, where $\alpha > 0$ reflects the technological improvement. Inserted in Equation (6) is this:

$$N_1 = cY + (ce^{-\alpha T})Ye^{-rT} + \cdots + (ce^{-\alpha\infty T})Ye^{-r\infty} = \frac{cY}{(1 - e^{-(r+\alpha)T})} \tag{7}$$

As can be seen from Equation (7), technological progress that gives lower turbine costs has the same effect as discounting with a higher interest rate and reduces the present value of the total investments.

The construction costs consist of roads, cables, any buildings and other costs. These works usually start several years before the turbines are installed. We assume that the construction investments' total amount is K and that these investments start z years before the turbine installation, and we further assume that the investment amount per unit of time is the same from time z, where $z < 0$ to time $t = 0$. This means that K/z is equal to the investment cost per unit of time. The net present value of the construction investments at time $t = 0$ is

$$N_2 = \frac{K}{z}\int_0^z e^{rt}dt = \frac{K(e^{rz} - 1)}{zr} \tag{8}$$

Wind power plants built in Norway or Sweden are often located in remote areas, and significant investments are often required to connect the plant to the central grid. These investments start n years before the turbine installation, and we assume that the investment amount per unit of time is the same from time n, where $n < 0$ to time $t = 0$. This means that L/n is equal to the investment cost per unit of time. The net present value of the grid investments at time $t = 0$ is

$$N_3 = \frac{L}{n}\int_0^n e^{rt}dt = \frac{L(e^{rn} - 1)}{rn} \tag{9}$$

Furthermore, we assume that the initial operating costs (including maintenance of the grid) per year are equal to D. We assume further that we have an annual improvement rate equal to β. Thus, the present value of the operating costs is equal to

$$N_4 = \int_0^\infty De^{-\beta t} \cdot e^{-rt} dt = \frac{D}{(r + \beta)} \tag{10}$$

Wind power production is not adjustable. If a large part of the electricity supply in the country comes from wind power, it can have major negative consequences if the wind stops blowing. Socially critical institutions, such as hospitals and defense or data centers, must install backup solutions if the production and import of electricity is too small to cover consumption and there is a risk of blackout. We assume that the initial investment in the backup solution is equal to B, where B is a function of the share of electricity that comes from non-regulated power production: $B = g(a, b)$, $g_a' > 0$, $g_b' < 0$ where a is the proportion of electricity that comes from non-adjustable power production and b is import capacity. We assume that the backup solution has a limited lifespan and must be renewed after k years, and that technological improvements, as explained above in Equation (7), reduce costs. The present value of all the investments related to the backup solution will then be

$$N_5 = \frac{B}{(1 - e^{-(r+\alpha)k})} \tag{11}$$

Developing wind power leads to environmental costs [24]. These costs must also be included. We assume a growth rate equal to γ on the value of lost nature. We assume that $\gamma < r$; otherwise, the costs will be infinite in a project with an infinite lifespan.

$$N_6 = \int_0^\infty (We^{\gamma t}) \cdot (e^{-rt} dt) = \frac{D}{(r - \gamma)} \tag{12}$$

Wind power development in Norway is based in its entirety on the hypothesis that man-made greenhouse gas emissions will lead to global warming that will have major negative effects [14]. Wind power development that makes it possible to reduce CO_2 emissions therefore has a value for society. We must include this in the total cost calculation. The size of the taxes paid on CO_2 emissions reflects the damage associated with CO_2 emissions. Oil companies in the Norwegian part of the North Sea now pay (March 2021) NOK 590 per tonne of CO_2 that they emit, and the companies have been notified by the government that this tax will increase to NOK 2000 per tonne. Our model is general; our aim is not to determine numbers on the parameters. This must be conducted when the model is used in practice, and then the CO_2 taxes can be a starting point.

We assume that the value of reduced greenhouse gas emissions is equal to C and that the value changes by a factor equal to μ for every unit of time, so that the value of the reduced greenhouse gas emissions in the period t is equal to $Ce^{\mu t}$. Thus, the net present value of the reduced greenhouse gas emissions will be

$$N_7 = \int_0^\infty (Ce^{\mu t}) \cdot (e^{-rt} dt) = \frac{C}{(r - \mu)} \tag{13}$$

The present value of the saved costs as a result of reduced greenhouse gas emissions must be deducted from the other cost components.

The present value of the total costs (N^*) thus becomes the sum of all the components mentioned above:

$$N^* = N_1 + N_2 + N_3 + N_4 + N_5 + N_6 - N_7 \tag{14}$$

Since we have assumed that reinvestments are made and that the project is perpetual, the annual costs are equal to rN^*. With a capacity factor equal to g, the number of hours of use per year becomes equal to h, where $h = g \cdot 8760$. Then, the expected production is equal to $h \cdot Y$. The long-term marginal costs, i.e., LCOE, will then be:

$$LCOE = \frac{rN^*}{Y \cdot h} \tag{15}$$

8. Conclusions

In Norway, electricity has been produced since 1877. High mountains and a lot of rain makes it possible to produce hydropower with lower costs than with other technologies. In 2020, the average electricity price including all taxes to households was 0.21 Euro in the EU while it was 0.13 Euro in Norway [26]. Hydropower has been and continues to be the dominant technology and more than 90% of the electricity used is produced by hydropower.

A characteristic feature of the Norwegian electricity market is the regular fluctuations during the day, week and year and the high consumption of electricity in households compared with other countries in Europe. While consumption per person in households in Norway in 2019 was 7529 kWh, the corresponding figure was 1581 kWh in the EU.

The development of wind power in Norway started in 1986, but it was only after the authorities introduced green certificates in 2012 that the development of wind power started to show strong growth, and in 2020, Norway was the country in Europe that installed the most wind power.

While more than 90% of hydropower production is owned by the state, municipalities or counties, more than 75% of wind power production is owned by private foreign investors. Ever since the development of wind power began, wind power producers have benefited from large subsidies. Since 2012, the subsidies have come in the form of the Norwegian-Swedish certificate scheme. This scheme will end during 2021 and it has not been decided that the scheme will be continued.

Despite the subsidy, the profitability of wind power producers has been poor. Of the 112 companies that were registered as wind power producers in 2019, 73 per cent had a negative operating profit, and the average operating profit was a modest NOK 17 million (approximately EUR 1.7 million).

In recent years, the development of wind power has been met with resistance due to the costs that the development has for the environment.

The price of electricity in the Nordic market has been relatively low since 2013. In the period of 2013–2020, the average system price was NOK 302 per MWh (about EUR 30 per MWh). The forecasts for consumption up to 2040 indicate that desired consumption will rise faster than the increase in production. This is likely to lead to higher electricity prices.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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