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Analysis of Norwegian Offshore Wind Power Production

Ranking wind farm locations using a composite index method

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Abstract

This thesis studies wind power production within the Norwegian Economic Zone, and analyzes the potential production of wind power farm locations outlined by the Norwegian Water Resource and Energy Directorate. Offshore wind farms have great potential as an energy source, but have high initial investment and maintenance costs, and finding the optimal locations for production is therefore essential. We use estimation data on offshore wind production, Norwegian energy consumption, and the filling degree of Norwegian hydropower plants. We perform a descriptive analysis, exploring how seasonal variations in wind power production relate to Norwegian electricity consumption, and how offshore wind can benefit Norwegian hydropower reservoirs. We find that in an average year, wind power production and electricity consumption will follow a similar seasonal cycle. The output potential of offshore wind power peaks during months with high electricity demand, which suggests that offshore wind is suited to Norwegian energy needs. Additionally, we find that wind power production and water levels in Norwegian reservoirs do not follow the same pattern. Water levels are at their lowest point during the spring, a period when the wind power output is still substantial. Therefore, we argue that offshore wind is a good complementary energy source for hydropower.

To analyze the potential of the suggested locations we use three indicators that reflect the capability of the locations in a composite index. The index ranks the locations based on power output, stability, and correlation with Norway's electricity consumption. The three locations scoring the highest are "Sørlige Nordsjø 2", "Sørlige Nordsjø 1", and "Nordøyan - Ytre Vikna", all located in the southern half of Norway.

Keywords – wind power, offshore, electricity, index, NVE

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation and purpose of the thesis

Norway has one of the world's longest coastlines, and marine areas five times as big as its land area (Regjeringen, 2021). These facts, combined with its long history in shipping and other offshore industries, makes Norway one of the nations with the largest potential in offshore wind. According to the Norwegian Water Resource and Energy Directorate (NVE), the power consumption in Norway will increase from 133 TWh in 2016, to 157 TWh in 2035 (Spilde et al., 2018). Norway has several options to meet the growing demand, and one of the options is to invest in, and develop an offshore wind industry. In May 2022 the Norwegian government stated that Norway has an ambition to allocate areas with the potential for 30 GW offshore wind production on the Norwegian continental shelf by 2040 (Regjeringen, 2022c). In December 2022, it was made clear by the government that they would open up for the construction of offshore wind power farms at the locations “Sørlige Nordsjø 2” and “Utsira Nord” during the first quarter of 2023 (Regjeringen, 2022b).

In December 2022, the Norwegian Minister of Trade and Industry stated that Norway will be a global leader in the offshore wind industry (Nærings- og fiskeridepartementet, 2022). However, if Norway is going to invest massively into offshore wind parks it is important that the most suitable areas for production are chosen to maximize the amount of electricity it will generate. Additionally, the initial investment cost for each offshore wind turbine is high, and making a highly informed choice in locating the most promising areas will be imperative (Bilgili et al., 2011).

The purpose of this master thesis is to identify general trends of offshore wind power, and to rank the NVE suggested locations by their relative potential. Using the findings from the data on offshore wind power, consumption, and water reservoirs we will attempt to shed light on how offshore wind parks are useful to include in the Norwegian energy mix. Additionally, we want to build an easy-to-read index that reflects the prerequisites of the locations to produce energy.

1.2 Research question

This thesis investigates the following research question:

Can the suggested offshore wind power locations be ranked using a composite index, and what factors are relevant indicators for a suitable wind power location?

The first part of the thesis is a descriptive analysis of the data. Here we found that wind power production and electricity consumption share a similar seasonal pattern, with higher values during the winter and lower during the summer. We also found a seasonal pattern of the filling grade of Norwegian hydropower reservoirs, which is at its lowest during spring and increases through the summer and fall. We used the insight gained from the descriptive analysis in the next part of the thesis, the construction of the index.

Following the descriptive analysis, we used a framework made by the Italian statisticians Mazziotta and Pareto to create an index of the suggested locations for offshore wind power farms. We outlined the phenomenon that were to be measured before the indicators were chosen and normalized. Finally, we weighted and aggregated the indicators into a composite index. Our findings from the index were that the two locations situated in the southern part of the North Sea, "Sørlige Nordsjø " 1 and 2 scored the best in the index, closely followed by one of our test location; "Sør for Mandal".

2 Background

In the following section, we present the timeline so far for offshore wind in Norway, followed by some positives and challenges regarding offshore wind, and lastly the reasons for why specifically Norway has a high potential in the offshore wind industry.

2.1 Why offshore wind power?

Today, Norway's main power source is hydropower, according to Graabak et al. (2017), this is made possible due to the nature of the country's mountainous terrain and heavy precipitation. However, this source can be affected by seasonal variations, but also years with lower precipitation, drought, or varying temperatures (Graabak et al., 2017). Especially in the spring the level of the reservoirs can drop to significantly lower levels (NVE, 2018). Due to this fact, and the growing demand for clean energy, Norway has to look for other potential sources to implement in their energy mix.

One such source is offshore wind. However, there are also other alternatives for green energy that Norway could rather invest in, and a natural comparison is onshore wind. Offshore wind technology has some positives, but also some challenges connected with it, compared to onshore wind.

2.1.1 Positive features

Firstly, the speed of the wind tends to be higher and more stable offshore due to the lack of obstacles in its path. This leads to a greater potential and stability in power production for offshore farms. The difference between 15 mph winds and 12 mph can double the energy output of a wind turbine (American Geoscience Institute, nd). Secondly, the offshore farms are less intrusive in the landscape, and potentially have a smaller impact on its local environment. A Swedish PhD thesis by Ek (2002), conducted a survey showing pictures of windmills in both the mountains and offshore, and people tended to prefer windmills located offshore. The aspect of intrusive noise was also a factor for people preferring offshore wind mills. Onshore wind farms tend to be perceived as disruptive for both the local environment and the populace (Ek, 2002). Thirdly, offshore wind has many of the same benefits as onshore wind. They provide renewable energy, consume no water, provide jobs, and do not emit pollutants or greenhouse gasses while running(American Geoscience Institute, nd).

2.1.2 Challenges

There are also some challenges associated with offshore wind, mainly, the cost of research, production, and maintenance of the farms. For fixed-foundation wind turbines, the cost has lowered dramatically in recent years, but for floating wind turbines the costs are still high (Eskeland et al., 2020). For instance, Equinor, as a world leader in offshore wind, has created the first commercial floating wind farm outside Scotland. Equinor (nd) state on their website that their focus is on lowering costs by streamlining production, technological improvements and scaling to make offshore wind a competitive energy resource. Due to the harsh environment at sea, there are also large costs connected to maintaining the farms (Equinor, nd). Furthermore, the effect on marine animals and birds is not fully understood and is an issue that will need further research (de Jong et al., 2020).

2.2 Timeline of offshore wind energy in Norway

In the fall of 2009, NVE received a mission from the Norwegian Ministry of Petroleum and Energy to propose possible locations for the establishment of offshore wind parks. In 2010 NVE released their suggestion of 16 locations along the coast based on technical and environmental criteria (NVE, 2010). In December 2012 NVE followed up with a strategic evaluation of all the suggested locations along the Norwegian coast that were included in the 2010 report (NVE, 2012). Included in the evaluation were several factors like cost, environmental and biological considerations, as well as the impact on the fishing and shipping industries. In 2020 the Norwegian government decided to open up for applications for the construction of a wind power farm at Utsira Nord and Sørlige Nordsjø 2 (Olje og energidepartementet, 2020). Utsira Nord is stated to be an area for technology development and demonstration projects, while Sørlige Nordsjø 2 is stated to be a potential source for export of electricity (Regjeringen, 2022a).

2.3 Norway as a leader within the field of offshore wind energy

There are several reasons why specifically Norway has the potential to be a leader in the offshore wind industry. In an analysis of future opportunities and challenges of offshore wind in Norway, published by Nilsson and Westin (2014), it is mentioned that Norway has the potential to export a large part of the supply chain for floating wind power. There are several reasons for this, firstly, Norway has a long heritage of working with similar structures as the ones needed for both turbines and foundations of the wind parks. Norwegian industry has experience using concrete and steelwork and has port structures that can make it possible to create the large structures needed. Secondly, Norway has a long history of shipbuilding, especially for specialized vessels, which will be essential in the construction and maintenance of the farms. Lastly, Norway has crucial competence in inter-array, substations, and export cable design, which will be important when planning and installing the stations. (Nilsson and Westin, 2014)

3 Literature Review

This section will examine the existing literature connected to our topic and position our thesis in relation to other studies done within this field.

A study by Solbrekke and Sorteberg (2022b) analyzed the Norwegian coast to find the areas most suitable for offshore wind farms. They found wind power suitability scores using a multi-criteria decision analysis framework. They considered many factors such as wind resources, techno-economic aspects, social acceptance, and more. For the analysis, a baseline scenario was set as a decision-maker that does not weigh one criterion heavily but chooses areas that are economically sound. In their analysis they found that southern parts of the Norwegian economic zone would be most suitable in general for offshore farms, taking into consideration the different scenarios that were analyzed (Solbrekke and Sorteberg, 2022b).

Our thesis is linked to the study by Solbrekke and Sorteberg in the form of a common data source, and by the purpose of the studies. Both studies are exploring the potential of offshore wind production within the Norwegian Economic Zone, albeit Solbrekke and Sorteberg's research is on a considerably larger scale. Their research relies on a broader foundation with several variables weighing in on their conclusions. They are also assessing the potential of the whole Norwegian Economic Zone, compared to our thesis which focuses on NVE's proposed locations. While Solbrekke and Sorteberg seek to investigate how well offshore wind power could perform along the Norwegian coastline, we seek to determine which of the proposed locations will perform well.

Italian statisticians, Matteo Mazziotta and Adriano Pareto have written several papers on how to measure multidimensional phenomena, both within the field of production and on socio-economic questions. Their first study describing their method was published in 2007 (Mazziotta and Pareto, 2007), unfortunately for the authors of this thesis, the paper was published in Italian, but they continued to use their method in a study from 2012, where the Mazziotta-Pareto Index (MPI) is compared to the Human Development Index and the Human Poverty Index (De Muro et al., 2012). In the same paper, they discuss the benefits and drawbacks of using multiple dimensions in measuring phenomena.

Our thesis build on the framework of Mazziotta and Pareto. By applying the MPI method to answer a research question that is not of a socio-economic nature, we argue that we contribute to the existing literature on measuring multidimensional phenomena. The reason being that we use a known method for creating an index, on a topic not previously researched with such a method.

4 Data

In this section of the thesis, the data used in the analyses will be presented. The offshore wind power production data from the Norwegian coast were gathered by a research group from the University of Bergen, and we were given a sample of their data that matched the relevant locations for this study (Solbrekke and Sorteberg, 2022a). The electricity consumption and water reservoir data are publicly available and gathered by government agencies or government agency-owned companies.

4.1 Wind power production data

As part of the aforementioned paper by Solbrekke and Sorteberg, they developed a dataset that gave them the possibility to estimate how much wind power could be generated within any 3x3 km grid inside the Norwegian economic zone. Their dataset, called the NORA3-WP is based on data from the Norwegian Meteorological Institute and a data set called NORA3. NORA3-WP has data on the form of watts per hour that could be produced at that location during a time span from 01.01.1996 to 31.12.2019 (Solbrekke and Sorteberg, 2022a). The original form of the data was in watts per hour, so we converted the data to MW per hour to fit the format of our other data by dividing them by a million.

For this thesis, we have extracted the locations of the areas that NVE have assessed from the NORA3-WP dataset using their geographic coordinates. Additionally, we included three areas that were not assessed by NVE, in total 19 locations. The reasoning for this inclusion was to investigate whether there are any significant differences between larger regions of the ocean outside Norway. Figure 4.1 presents the areas that are included in our analysis. The red dots mark the areas that are not a part of NVE's consideration. A detail worth mentioning is that we only have data for a specific geographical point within the 3x3 km squares and that the actual wind power farms will stretch beyond this area.

Figure 4.1: Suggested locations for offshore wind power farms

4.2 Electricity consumption data

The consumption data is collected and published by Statnett, a company owned by the Norwegian Ministry of Petroleum and Energy (OED) (Statnett, nd). They have estimated the consumption based on the sum of electricity produced and imported, and subtracted electricity exported. This seems to be the best estimation of Norwegian energy consumption publicly available. The available data spans from 01.01.2007 to present date, with hourly entries of the total MWh consumed in the Norwegian market.

$$Consumption = Production + Import - Export$$

4.3 Water reservoir data

The water reservoir data contains the average filling degree of Norwegian reservoirs. The data is gathered on a weekly basis from 489 most important reservoirs in Norway, and an average percentage is calculated (NVE, 2019). The total reservoir capacity is annually updated. The time range available is from 1995 to present day. This data is relevant for finding the peak periods when it is most necessary to have supplementary power sources available, such as offshore wind.

5 Descriptive Analysis

This section will present a descriptive analysis of the presented data. Firstly, general trends and potential cyclic variations of wind power will be presented. Secondly, we examine the relationship between wind power production and consumption in the Norwegian power market. Thirdly, the data for the locations are described and how it affects the creation of the index. The available time dimension for the data used in this thesis varied among our data sets, thereby limiting us to use data from the period 2007 to 2019. When we refer to production in general, the base data is an hourly mean of production from all locations included in the data. We argue that this can be used when examining general trends for offshore wind power since the data is spread along the Norwegian coast. When specific location data is used it will be clearly stated.

5.1 Offshore windpower production

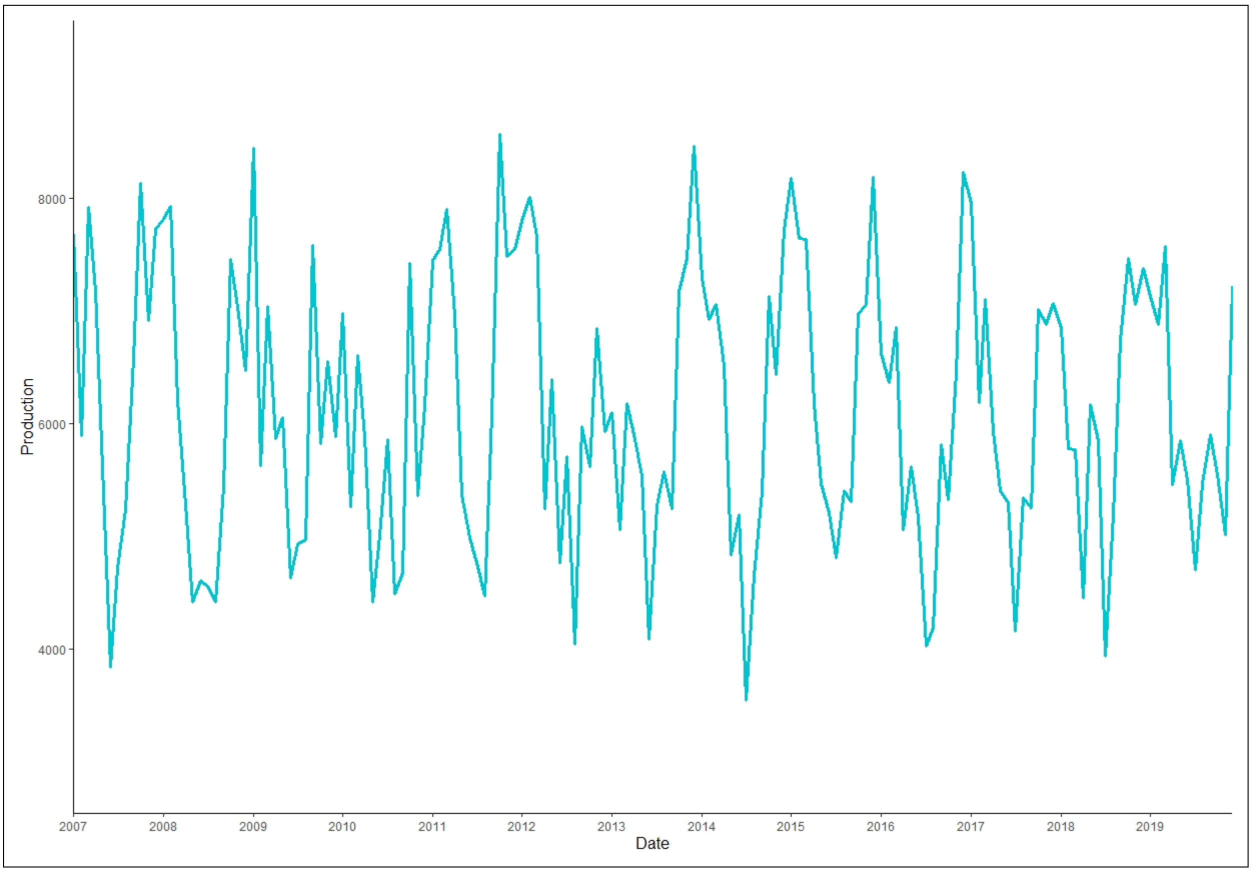


Figure 5.1: Monthly production, 2007-2019

In figure 5.1 the average production per month for the whole twelve-year timespan is presented. We observe a pattern of seasonal variation with the highest points during the winter, and the lowest during the summer. This is a natural observation since a higher temperature gradient leads to higher wind speeds and therefore more power output from the turbines (Miller, 2019). The same trend can be observed in appendix A1.3, which is a boxplot of the average hourly production, per month over a year. We observe the same dip in the mean output during the summer.

In appendix A1.5 a boxplot of the mean hourly production over all the years is presented. The mean is almost equal during all hours, and the sizes of the boxes are also very similar. Over a longer period, the power production seems to be potentially very stable, but one has to take into account that there are over 110 000 hourly observations. Even though it seems very stable, many observations also lie outside the boxes, the boxes being 50 % of the observations. Additionally, in figure 5.2 and appendix A1.4 we present two histograms with a count of the hourly production, respectively for one and all the NVE locations. These histograms show the number of hours a location has produced at a given capacity, with the minimum being zero and the maximum 15 MW. The data shows that most of the time the turbine produces either at maximum capacity, or nothing at all. One can assume the reason for this is that a certain amount of wind speed is needed to reach maximum capacity, and wind above that point does not produce more power.

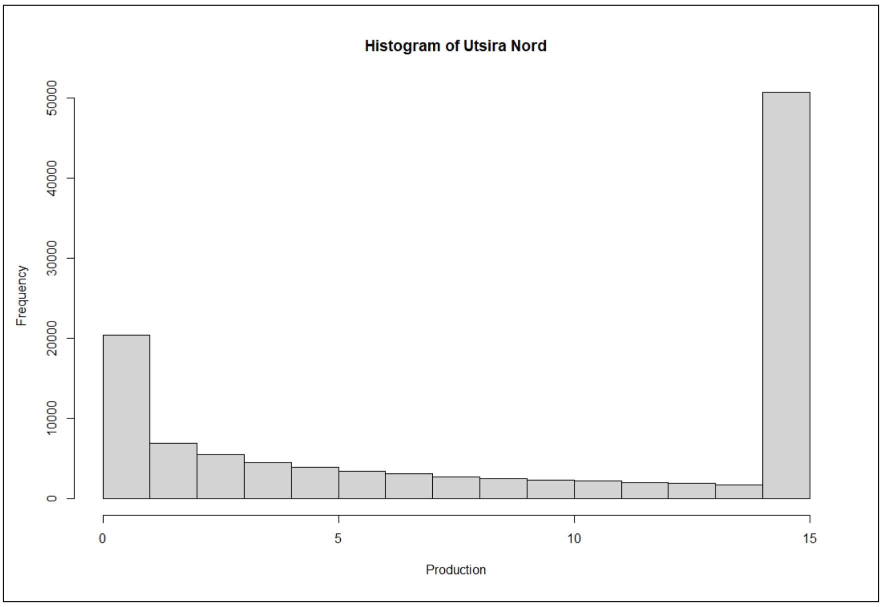


Figure 5.2: Histogram of location Utsira Nord

5.2 Production and consumption

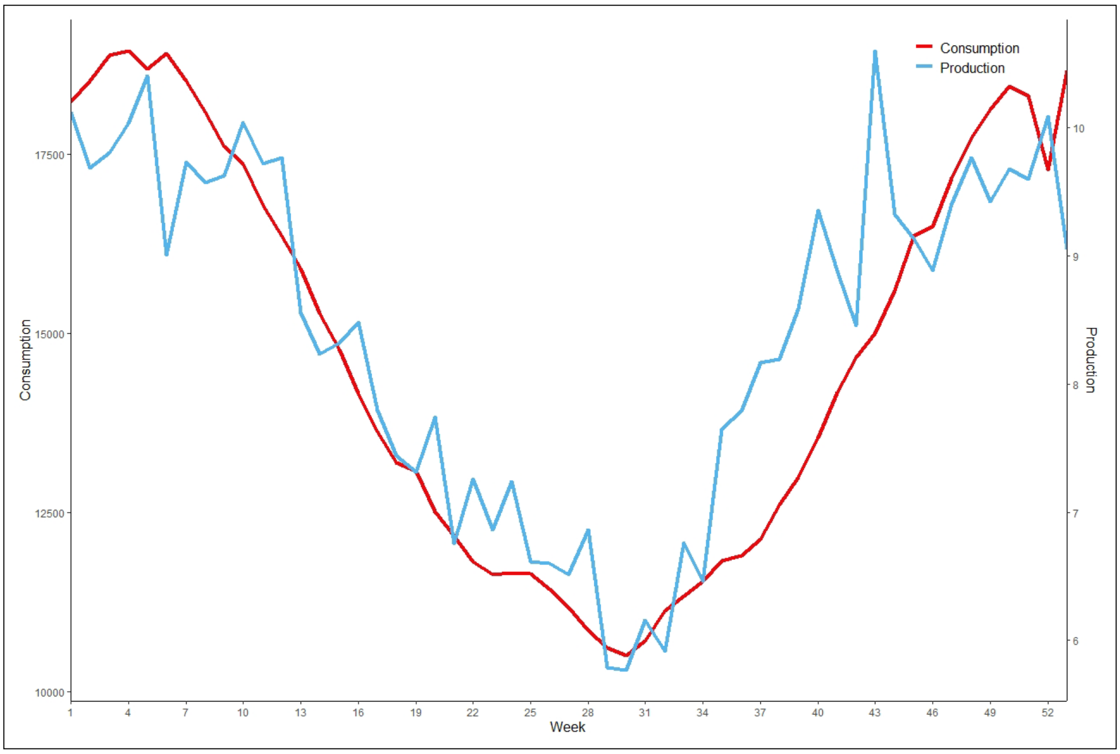


Figure 5.3: Average weekly production and consumption, over a year

In figure 5.3 we present a graph with the average monthly production and consumption during a year. Both graphs show a similar trend during the year, with a peak during the winter, and a dip during the summer. Consumption is lower during summer due to higher temperatures and more hours of sunlight, leading to a reduced need for lighting and warming of buildings (PJM, nd). The opposite is true for winter months. This is an interesting observation, since it is positive for offshore wind as an energy source that the output of offshore wind seems to be the highest when consumption is highest.

5.3 Production and water reservoir level

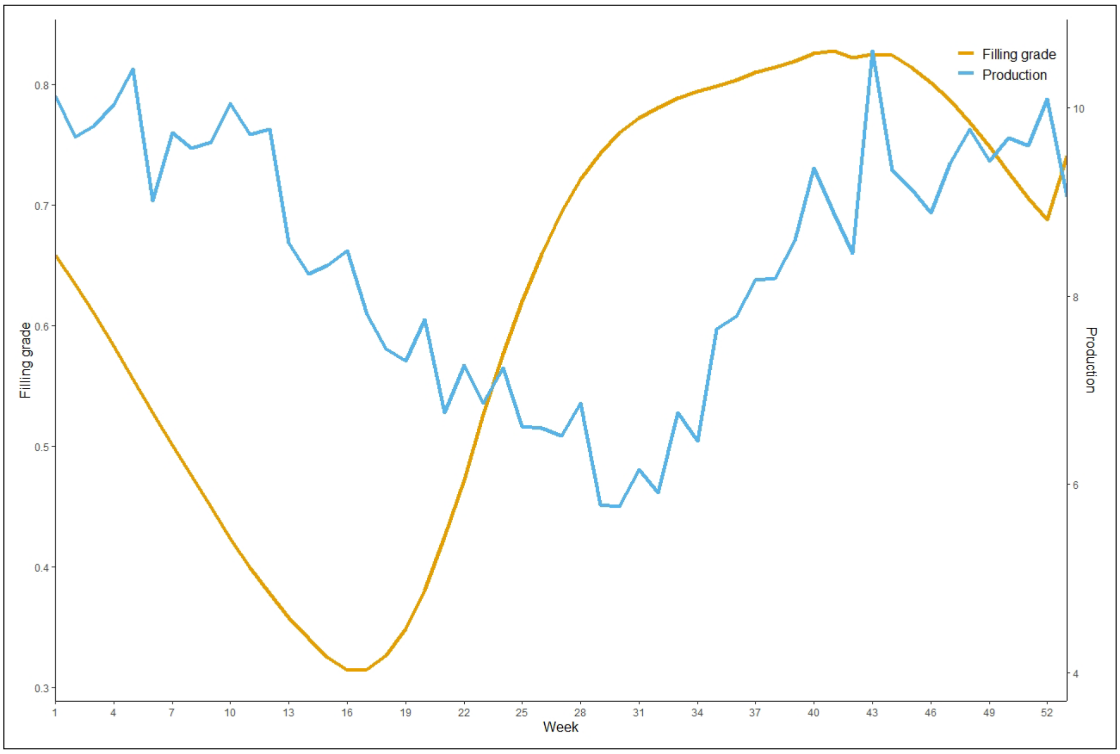


Figure 5.4: Average weekly production and filling grade Norwegian reservoirs, over a year

In figure 5.4 we present a graph with weekly water reservoir levels, and weekly average production. The reasoning for including this is to investigate if offshore wind can be a good substitute for hydropower in the period with low water levels. Water levels are sinking until weeks 15-16, before the reservoirs fill up again due to the meltwater and more precipitation during the spring and summer (Mjønerud, 2019). Production is not at its highest during the weeks with lower water levels, but reaches its lowest point 12-14 weeks after the water levels. This is an interesting observation with regard to offshore wind power as a complementary source in the Norwegian energy mix.

5.4 NVE locations

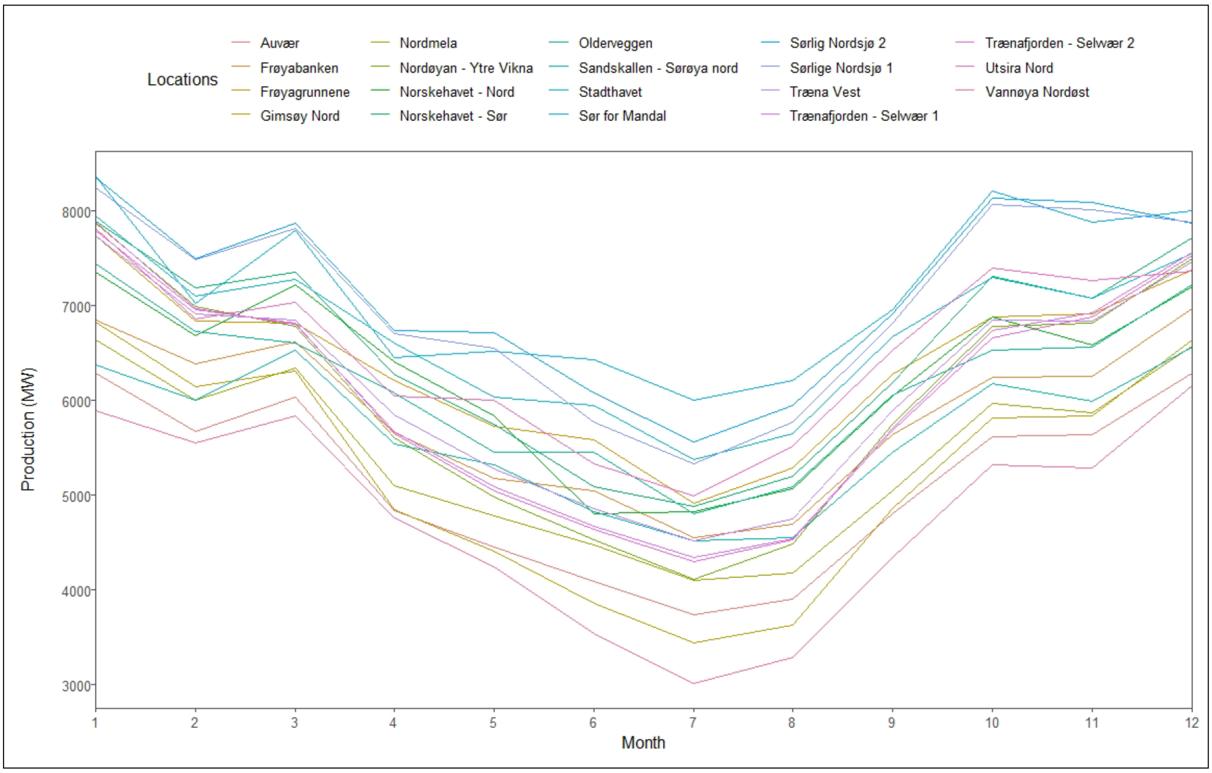


Figure 5.5: Average monthly production, all locations

Firstly, we present in figure 5.5 a plot with all locations and their respective graph for average monthly power production. This plot shows the same seasonal trend as observed for all power data for all locations, but we see that there are differences in potential output from each location. It is interesting that the trend for all locations seems so similar since the data is extracted from different locations along the whole Norwegian coast.

Secondly, in appendix A1.4 a plot with histograms for each location is presented. Our raw data for production and consumption inherently has a multimodal distribution. Following the central limit theorem (Rouaud, 2013), aggregating the data leads to a near normally distributed data set for all locations, but this is not the case for the consumption data (A1.1). The multimodal nature of the consumption data can potentially limit the choice of correlation coefficients used to measure correlation between production and consumption.

Thirdly, in appendix A1.2, a scatterplot of the correlation between hourly production and hourly consumption, for each location, is presented. From this we can see that there are no clear linear relationships, but there seem to be tendencies towards a monotonic relationship between production and consumption (Gupta, 2022).

6 Empirical Approach

One goal of this thesis is to find the best location for Norwegian offshore wind farms based on the recommended areas from NVE. In this section, we will present our empirical approach to answering this part of the research question. First, correlation and the Spearman correlation coefficient will be explained due to its relevance in one of the factors of our index. Secondly, a general approach on how to create an index is presented, and lastly, the Mazziotta Pareto Index, its methodology, and its computation is presented.

6.1 Spearman's rank-order correlation

Correlation is a statistical measure that expresses to which extent two variables are linearly related, and is a common tool describing simple relationships between variables without implying any cause and affect of the relationship (Akoglu, 2018). One method for measuring correlation is the Spearman's rank-order correlation, or Spearman correlation coefficient. The Spearman correlation is a nonparametric version of the Pearson correlation, and it measures the strength and direction of association between two variables (Lærd Statistics, nd). The Spearman correlation is used when one or more of the assumptions of Pearson correlation is not met, which is the case with our data. According to Gupta (2022), Spearman correlation measures the monotonic relationship between variables rather than the linear relationship. A monotonic relationship is present if the two variables either 1) increase together, 2) as X increases, the value of Y decreases, or 3) the relationship is non-monotonic if X increases and Y sometimes increases or sometimes decreases (Gupta, 2022).

The Spearman correlation coefficient is chosen as the measurement of correlation in cases where one does not observe clear linear relationships from the scatterplots, but rather clear monotonic relationships or tendencies. The coefficient has a value between -1 and 1, where 1 is perfect association of rank, 0 is no association of rank, and -1 is perfect negative association of rank. The formula for the Spearman correlation without paired ranks is as follows:

$$\rho = 1 - (\frac{(6\sum d_i^2)}{n(n^2-1)}$$

Where: ρ is the Spearman correlation coefficient, d_i is the difference between the two ranks of each observation, and n is the number of observations.

6.2 Composite Indices

One definition of an index is "a sign or measure that something else can be judged by" (Oxford Learners Dictionary, 2022). According to Tardi (2022), a composite index is a statistical tool that groups together different indicators or factors in order to create a representation of overall market performance (Tardi, 2022). They are also commonly used to measure and monitor differences and development of socio-economic phenomena. The method is used as a tool to aggregate multiple indicators of a phenomenon into one comparable indicator, i.e., in a group of countries or regions (Booysen, 2002).

The literature on indices is vast, but in the case of this thesis, we base our theoretical approach on two articles. The first is "Methods for constructing composite indices: One for all or all for One?" by Mazziotta and Pareto, which presents a general framework on how to construct composite indices (Mazziotta and Pareto, 2013). The second one is a paper from 2012 called "Composite Indices of Development and Poverty: An Application to MDGs" where a specific approach on how to generate an index is presented, called the Mazziotta Pareto Index (MPI) (De Muro et al., 2012). Even though both of these papers, and most of the literature on composite indices, are focused on sosio-economic measures, we argue that the method used in creating the MPI is relevant for ranking offshore wind locations. The reasoning for this is that the nature of the indicators used in sosio-economic indices, such as the MPI, is numeric, which is also the case for our data. Therefore, the method will also be applicable when creating a composite measure of numeric indicators that are relevant for ranking offshore wind locations. The MPI method has also been used in a competitiveness analysis of the EU wine market (Greco et al., 2016).

6.3 Constructing an index

The aforementioned paper from 2013 presents a framework for constructing indices and explains the different options available when deciding what to include, which methods to use when normalizing the data, and how to weight the different factors when constructing the final index (Mazziotta and Pareto, 2013). There is no universal method for creating composite indices, and there are several factors to take into consideration when constructing an index, such as accessibility of data and the desired complexity of the index, and each case must be determined by the application. In our case, we want to create an index that is easy to understand, but also gives a clear, numerical outcome that represents the factual truth of which area is most suited for production.

The article defines a framework and four steps to take into consideration when constructing an index. The steps given in the article are as follows:

1. Defining the phenomenon to be measured
2. Selecting a group of individual indicators
3. Normalizing the individual indicators
4. Aggregating the normalized indicators

The first step states that it should be clear and concise what the given index is measuring. An example is the Human Development Index, which is “a summary measure of average achievement in key dimensions of human development”, according to the United Nations Development Program (UNDP, nd). The index needs to have given, clear boundaries for what it actually measures in order for it to be applicable when discussing the given phenomenon, and also to make sure it is not used out of context. For instance, the UNDP states that the HDI does not reflect on inequalities, poverty, empowerment and more.

The second step focuses on how the indicators should be selected according to their relevance, analytical soundness, and accessibility. In the relevance and analytical soundness of the indicator lies the fact that the indicators must be contributing to explaining the phenomenon it is trying to measure. One should also take into consideration how feasible it is to keep the indicators updated over time, in order to maintain the relevance of the index. Continuing using the HDI as an example, it has three indicators, which are life expectancy at birth, years of schooling for adults over 25, and gross national income per capita. These are all indicators that are deemed relevant, analytically sound, and are accessible for most of the nations of the world.

The third step is deciding which normalization method to use. Since the nature of the data the indicators are based on can vary in both scale and range, the indicators need to be normalized such that they are comparable. There are several different normalization methods, such as the min-max transformation used in the HDI, or the z-score applied in the MPI.

The last step is how one should combine the different indicators into the final composite index, and how each component should be weighted. There are a number of methods for aggregating, and they can lead to different outcomes. The HDI uses an equal weighting method, which implicitly states that the UNDP regards the indicators as equally important towards measuring human development. There are also several other methods of aggregating indicators, such as “principal component analysis”, “factor analysis” and “benefit of the doubt approach” (Gan et al., 2017).

6.4 The Mazziotta-Pareto Index

The Mazziotta-Pareto index is developed for cases where a multidimensional index is needed to measure a complex phenomena. A multidimensional index can offer a more nuanced understanding of an event than a unidimensional one. Another distinctive feature of the Mazziotta-Pareto index, is the introduction of penalties to “unbalanced” indicator values. It is an index specifically for the use of indicators that are non-substitutable, or non-compensatory, meaning that no high result for one indicator can compensate for a low score on another, and vice versa (De Muro et al., 2012).

The MPI and its method is designed in order to satisfy the following properties:

1. Normalization of the indicators by a specific criterion that deletes the unit of measurement and the variability
2. Synthesis independent from an “ideal unit”, since a set of “optimal values” is arbitrary, non-univocal and can vary with time
3. Simplicity of computation

De Muro et al. (2012) argue that the distributions of the indicators, even though they are measured in different units, can be compared if their standard deviations are changed. This is done by normalizing the indicators into a common scale with a mean of 100 and a standard deviation of 10. Each indicator will then range between 70-130. After the normalization, when the acquired z-scores are aggregated into a final index, a penalty function is introduced for each area based on the variability between the z-scores. De Muro et al. (2012) use a coefficient of variation to measure the variability, and this is used to penalize units for having an "unstable" relationship between its indicators. The result is that the method favors the units, mean and standard deviation being equal, that have a greater balance between its indicator values, it also eliminates influence by outliers (De Muro et al., 2012).

6.4.1 Computing the MPI

In this section, we present how the MPI is computed. Firstly, how the normalization is computed, followed by how the units are aggregated. The following method is retrieved from the paper "Composite Indices of Development and Poverty: An Application to MDGs" (De Muro et al., 2012).

6.4.1.1 Normalization

Let $X = \{x_{ij}\}$ be the matrix with n rows (number of locations) and m columns (number of indicators) and let M_{x_j} and S_{x_j} denote the mean x and the standard deviation of the j-th indicator:

$$M_{x_j} = \frac{\sum\limits_{i=1}^{n} x_{ij}}{n}; \qquad S_{x_j} = \sqrt{\frac{\sum\limits_{i=1}^{n}(x_{ij} - M_{x_j})^2}{n}} \tag{6.1}$$

The standardized matrix $Z = \{z_{ij}\}$ is defined as follows:

$$z_{ij} = 100 \pm \frac{(x_{ij} - M_{x_j})}{S_{x_j}} 10 \tag{6.2}$$

where the sign ± depends on the relation of the j-th indicators with the phenomenon to be measured (+ if the individual indicator represents a dimension considered positive and if it represents a dimension considered negative).

6.4.1.2 Aggregation

Let cv_i be the coefficient of variation for the i-th units:

$$cv_i = \frac{S_{z_i}}{M_{z_i}} \tag{6.3}$$

where:

$$M_{z_j} = \frac{\sum_{j=1}^{n} z_{ij}}{m}; \qquad S_{z_j} = \sqrt{\frac{\sum_{j=1}^{m} (z_{ij} - M_{z_j})^2}{m}} \tag{6.4}$$

Then, the generalized form of MPI is given by:

$$MPI_i^{+/-} = M_{z_i}(1 \pm cv_i^2) = M_{z_i} \pm S_{z_i} cv_i \tag{6.5}$$

where the sign of the penalty (the product $S_{z_i} cv_i$) depends on the kind of phenomenon to be measured and then on the direction of the individual indicators.

If the indicator is increasing or positive, in other words, increasing values of the indicator responds to positive cases of the phenomenon, which is the case for offshore wind locations, one uses the MPI.

7 Empirical Analysis

In this section we present the analysis of NVEs wind farm locations, and its results. Firstly, the phenomenon to be measured is defined. Secondly, an explanation of the choice and creation of the indicators is given. Thirdly, the MPI method for normalization and aggregation is applied on the data. Lastly, the scores and rankings of the individual locations are presented.

7.1 Defining the phenomenon

Following the aforementioned framework of Mazziotta and Pareto (Mazziotta and Pareto, 2013), we start by defining the phenomenon to be measured. The phenomenon in the case of our thesis must align with the research question. So, the index should create a ranking of the given offshore wind farm locations, based on potential production, consumption, and the correlation of these factors. It should measure and give a good representation of the difference between each location, while being easy to understand and interpret by offshore wind stakeholders. The last point is important for the paper to potentially be useful for policymakers, investors or other future researchers that will study the same phenomenon.

7.2 Choice and creation of the indicators

The next step of the framework is to identify which indicators are needed to measure the given phenomenon, and find or create these indicators. After debating different indicators, we landed on three indicators that reflect different aspects one has to take into consideration when choosing between the locations. The three indicators are as follows: 1) average yearly energy production in a given location, 2) the standard deviation of hourly energy production, and 3) the correlation between Norwegian energy consumption and a given location's energy production.

The first indicator is “average yearly energy production for a given location”. The indicator is created by aggregating the total sum for each year, and taking the average over the twelve-year time period. The reasoning for this choice is that for a location to be a valued option it should produce as much energy output as possible, which naturally is important when considering where to position a wind farm. The yearly average is used because it gives a good representation of how much a location produces over a fairly long timeframe.

The second indicator is “the standard deviation of hourly energy production”. It is created by computing the standard deviation of the hourly production, over all hours between 2007 to 2019. The reasoning behind the choice is that, optimally, a power production source should be relatively stable and predictable. It is not optimal if a location produces a lot of energy in a few hours of the day and is dormant for the rest. Therefore, we include the standard deviation as an indicator in order to measure how stable each location is. The reasoning for using the hourly time frame is to capture the daily variance, and to favor locations with stable hourly production.

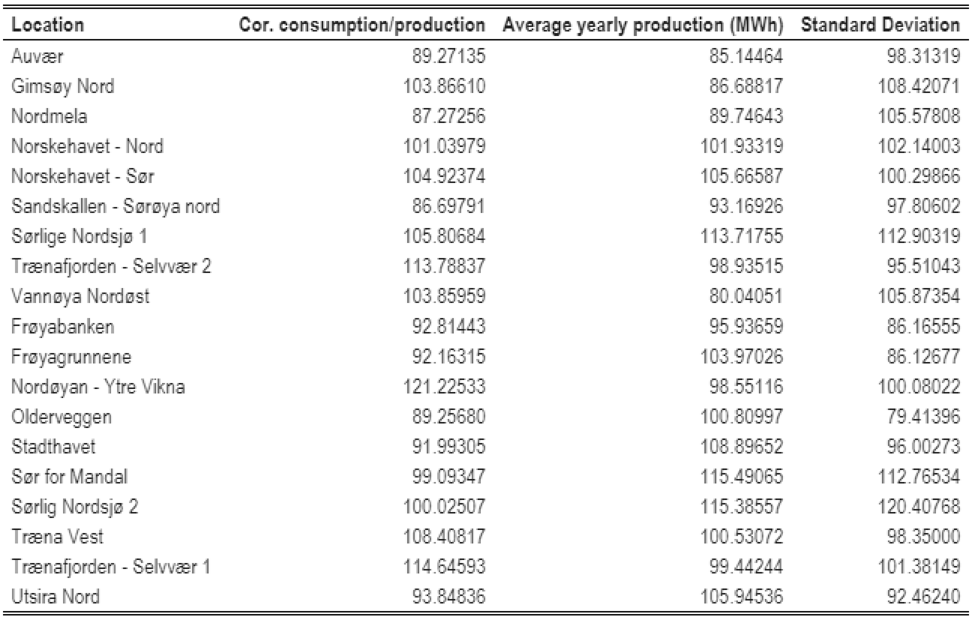
The third indicator is “correlation between Norwegian energy consumption and a given location’s energy production.” It is created by computing the Spearman correlation between hourly Norwegian energy consumption and hourly production for a given location. The reasoning for including this indicator is that electricity has to be produced as it is consumed, because large-scale electricity storage is not a viable solution as of now (Kobayashi-Solomon, 2022). Therefore, a location should be favored if its production correlates with when electricity is consumed. The indicator is capturing the fact that it is positive if a location produces large quantities of electricity when large quantities of electricity are consumed, and the same is true for low production with low consumption since overproduction is not preferable. It should be noted that the actual values for correlation will not be high, the highest being around 0.5, but in our case, it is the relative comparison between locations that is important.

A fourth indicator was considered that would include the average production in a time period of 10 weeks when the water reservoirs in Norway are at their lowest. This was omitted because we found that the correlation between the locations that had the highest yearly average production, and the locations that had the highest average production in the 10 weeks were almost 1. If it were to be included it would technically double the weighting of production in the index.

7.3 Normalization and aggregation of indicators

The third step in the framework is normalization of the indicators. The normalization process follows the formula for MPI given in section 6.4.1, and is computed in R with the function ci_normalized from compbind package. In table 7.1 a matrix of the Z scores for each location and indicator is presented. A general remark is that we observe that the Z scores varies inside the expected range of 70:130. It is important to remember that these are relative scores, so even though for example Nordøyan has a high z-score for correlation, the correlation coefficient is 0.52. Nevertheless, for the purpose of ranking the locations the relative z-score works well.

Table 7.1: Z-score for indicators

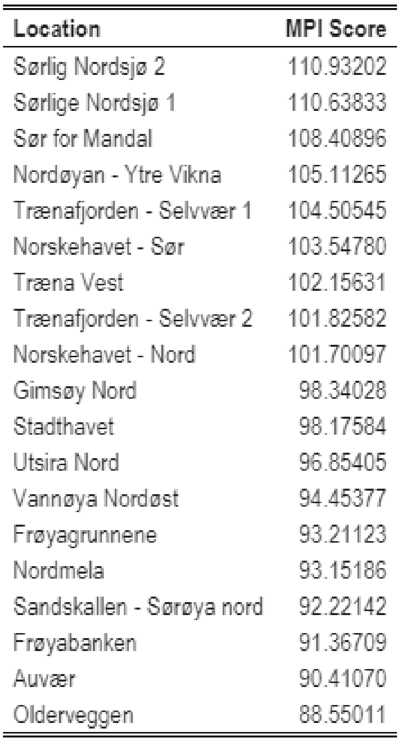


Location	Cor. consumption/production	Average yearly production (MWh)	Standard Deviation
Auvær	89.27135	85.14464	98.31319
Gimsøy Nord	103.86610	86.68817	108.42071
Nordmela	87.27256	89.74643	105.57808
Norskehavet - Nord	101.03979	101.93319	102.14003
Norskehavet - Sør	104.92374	105.66587	100.29866
Sandskallen - Sørøya nord	86.69791	93.16926	97.80602
Sørlige Nordsjø 1	105.80684	113.71755	112.90319
Trænafjorden - Selvvær 2	113.78837	98.93515	95.51043
Vannøya Nordøst	103.85959	80.04051	105.87354
Frøyabanken	92.81443	95.93659	86.16555
Frøyagrunnene	92.16315	103.97026	86.12677
Nordøyan - Ytre Vikna	121.22533	98.55116	100.08022
Olderveggen	89.25680	100.80997	79.41396
Stadthavet	91.99305	108.89652	96.00273
Sør for Mandal	99.09347	115.49065	112.76534
Sørlig Nordsjø 2	100.02507	115.38557	120.40768
Træna Vest	108.40817	100.53072	98.35000
Trænafjorden - Selvvær 1	114.64593	99.44244	101.38149
Utsira Nord	93.84836	105.94536	92.46240

7.4 Aggregation of indicators and results

The fourth step is aggregation of the indicators. The aggregation process follows the formula for the MPI given in section 6.4.1, and is computed in R with the function ci_mpi from the compbind package. The results of our analysis and the final index are shown in table 7.2. Among the suggested NVE locations, Sørlige Nordsjø 1 and 2 have the highest scores and therefore are the best choices according to the index, closely followed by one of our test locations, Sør for Mandal. Two noticeable points are that Sørlige Nordsjø 2 scores the highest, while Utsira Nord is in the lower half of the ranking. These are the only locations where it is possible to submit a license application for potential projects as of the writing of this thesis.

Table 7.2: Mazziotta-Pareto Index Scores



Location	MPI Score
Sørlig Nordsjø 2	110.93202
Sørlige Nordsjø 1	110.63833
Sør for Mandal	108.40896
Nordøyan - Ytre Vikna	105.11265
Trænafjorden - Selvvær 1	104.50545
Norskehavet - Sør	103.54780
Træna Vest	102.15631
Trænafjorden - Selvvær 2	101.82582
Norskehavet - Nord	101.70097
Gimsøy Nord	98.34028
Stadthavet	98.17584
Utsira Nord	96.85405
Vannøya Nordøst	94.45377
Frøyagrunnene	93.21123
Nordmela	93.15186
Sandskallen - Sørøya nord	92.22142
Frøyabanken	91.36709
Auvær	90.41070
Olderveggen	88.55011

8 Discussion

In the following section, we will discuss the findings of the descriptive analysis, the ranking, and the study's limitations based on indicators and method choice.

8.1 Findings of descriptive analysis

In the descriptive analysis of offshore wind power, we find that there is a seasonal cycle for wind power production, which is backed up by literature on yearly wind cycles. The power output seems stable over several years with peaks during winter and dips during the summer months. Even though the average production is lower during summer, it is important to remark that it is not extremely low. One turbine has an output of around 4000 MW in the lowest months, while the peaks are over 8000 MW, seen in figure 5.1. So the difference is quite substantial, but the turbine will still produce a considerable amount of power during the summer, on average for all locations. Therefore, over a longer time period we argue that offshore wind power is a stable source of energy. On the other hand, we see in appendix A1.4 that most of the hours the turbine produce at either zero or maximum capacity. This is an indication that the daily production is not as stable.

In figure 5.3 we find that on average, the yearly trend for offshore wind production and Norwegian energy consumption is similar. This finding says that offshore wind power production is peaking when the demand for energy is high, which is an argument for including offshore wind in the Norwegian energy mix. The reasoning is that offshore wind can be a complementary energy source, together with hydropower, at times with high demand. It can also be argued that it is positive that the power production is low when demand is low so it does not lead to overproduction. But, most farms will probably be able to either export the overproduction, or one can save hydropower by using offshore wind at times when offshore power production is high. In general, it seems that offshore wind production is conveniently suited to Norwegian energy consumption.

In figure 5.4 we see how the offshore production follows the yearly average for water reservoirs. We wanted to find whether offshore wind could also be a good substitute for hydro power during the weeks with low water levels in the reservoirs. From the plot, we can see that the production is still substantial during the low water level weeks, but it can not be argued that it is a definite substitute during these weeks. Subsequently, it is not realistic for offshore wind to produce the same amount of power as the hydro plants in Norway, at least not in the foreseeable future. Therefore, we argue again that offshore wind power is a good complementary source. It can potentially “flatten” the graph for the water levels by reducing the amount of water used for power production during the year, but it can not be a complete substitute for hydro power at this point.

8.2 Findings of the ranking

Based on our index and its results we find that the location Sørlige Nordsjø 2 is the most suitable location based on energy production and stability, and correlation with Norwegian energy consumption. This is one of the areas that NVE has selected for future development and it is also stated that its location is relevant for electricity export (Regjeringen, 2022a). Our findings show that this location has high z-scores for both production and stability, which makes it a good source for general electricity production and aligns with the location as a potential export source.

Following Sørlige Nordsjø 2 is Sørlige Nordsjø 1, which is logical due to their relative proximity. One can assume that the values for production are similar, and therefore argue that this location is also suitable as a potential export source. We also argue that based on its location it could be suitable as a clean energy source for other offshore installations in the North Sea, or as an energy source for the mainland of Southern Norway because of its geographical position.

The second location that NVE has selected for potential development is Utsira Nord. This location ranked 12th of the 19 locations, with a score of 96.65. Based on these findings, Utsira seems to be a deviant choice for an offshore wind farm compared to other locations. However, it has been stated that Utsira Nord will be used for demo projects and testing of technology, so one can assume that its closeness to the shore and other factors was deemed more relevant than the factors of this thesis.

The location Nordøyan - Ytre Vikna is ranked 4th, with a score of 105.11. This area is located outside Central Norway, and based on our findings could be a potential electricity source for Central and Northern Norway. The reasoning for this is its high ranking, but also its location that is much farther north than most of the other locations that ranked well. It is also located close to shore which in most cases is a positive factor.

As mentioned in the empirical analysis, a fourth indicator based on when Norwegian water level reservoirs are low was considered. We tried to find a different approach on how to include this as a factor, but concluded that if a location has a high general production it also has a high production in the critical time window. The finding is included because we argue that if a location could be a viable alternative source of electricity when the capacity of hydropower plants is low, it could be a strong indicator of an attractive area for wind power farms. However, it seems that locations with high production generally keep this advantage throughout the year. This could imply that offshore wind is not the best alternative as a completely reliable source when water reservoirs are at critical levels.

The three test locations that were included in the study, along with NVE's locations, all received a higher than average score. Interpreting this result, it suggests that there also are other areas in the Norwegian Economic Zone that, purely from a wind speed and density perspective, have the qualities of a potential offshore wind power farm. However, as we have mentioned earlier, there are a lot of factors that play a part in what areas are actually seen as feasible.

8.3 Implications of the study

One part of our study focuses on how productive the suggested NVE areas are. Earlier research, such as the paper from Solbrekke and Sorteberg (2022b), shows that offshore wind farms seem to have the highest potential in the South of Norway, which aligns with our findings (Solbrekke and Sorteberg, 2022b). Our study differentiates itself from earlier studies by considering the correlation factor between consumption and production, and how this can affect the choice of location. Additionally, the study examines one specific part of the complex choice of choosing where to build wind farms, by creating an index that is easy to understand and interpret for both policymakers and other stakeholders interested. Lastly, from what we have found, there are no other public studies that specifically target the suggested areas by NVE, and which of these has the best potential for offshore wind production.

In general, we argue that the index does what it is intended to do. It has created an understandable ranking for the proposed locations from NVE, based on production and consumption factors. Even though the scope is fairly limited, it is valuable to have information on which locations have the best potential for energy production. On the other hand, the choice of locations is complex and takes into consideration many factors outside only the highest production, such as the interest of fisheries or closeness to protected areas. The subject of this thesis and the index is to answer one of the many questions one needs to ask when deciding on which locations are best for offshore wind farms.

8.4 Limitations of the study

While the method used in this study is arguably well suited for comparing relative performances between areas or regions, indices are a simplification of complex, real-life phenomena. In the case of this study, the index only measures relative performance, and fails to address how well the locations perform overall. As mentioned earlier in the thesis, the purpose of an index is to illustrate a result in a readable manner without demanding a lot of statistical insight from the reader. However, the calculations made on the way could result in a loss of information from the original data. Furthermore, the selection of variables is highly subjective which also adds to the risk of losing valuable information in the final result.

To reflect the complexity of measuring and ranking wind power farm locations, one could argue that a greater amount of indicators, and a larger span between what they intercept would make the index more comprehensive. However, additional or different indicators would mean that the phenomena this index is trying to explain would no longer be relevant. Additionally, with a less specific case to study, the end result would not be as accurately describing the performance characteristics of the locations.

9 Conclusion

This thesis concludes that among the suggested wind farm locations by NVE, Sørlige Nordsjø 2 is the most suitable location for an offshore wind farm, based on the factors production, stability, and correlation with Norwegian consumption, followed by Sørlige Nordsjø 1, and Nordøyan - Ytre Vikna. This is based on the MPI method using three indicators of relevancy to create an index, ranking all suggested locations. Locations in the southern half of Norway score better, which aligns with earlier studies on the subject.

From the descriptive analysis, we found that offshore wind power production has a seasonal variation and that it follows the same trend as Norwegian energy consumption. Furthermore, offshore wind power production can not be seen as a substitute for hydropower. The reasoning is the unrealistic amount of power needed to be produced by the farms, in addition to the fact that the peaks of offshore wind production do not align with the timeframe when a substitute for hydropower is necessary. Rather, offshore wind can be a potential complementary energy source alongside hydropower in the Norwegian energy mix, due to its correlation with consumption, and being a relatively stable source over time.

Even though the scope of the thesis is narrow, we argue that our findings give a new insight into which locations could be developed next from a standpoint of optimal production. Subsequently, we have looked at how offshore wind as an energy source can be a good complement to the Norwegian energy mix. Lastly, we have used an index method to create a comprehensible ranking of possible wind power locations. The index provides new insight into the debate on where to construct offshore wind farms.

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Appendix

A1 Figures

Figure A1.1: Histogram of weekly aggregated production and consumption

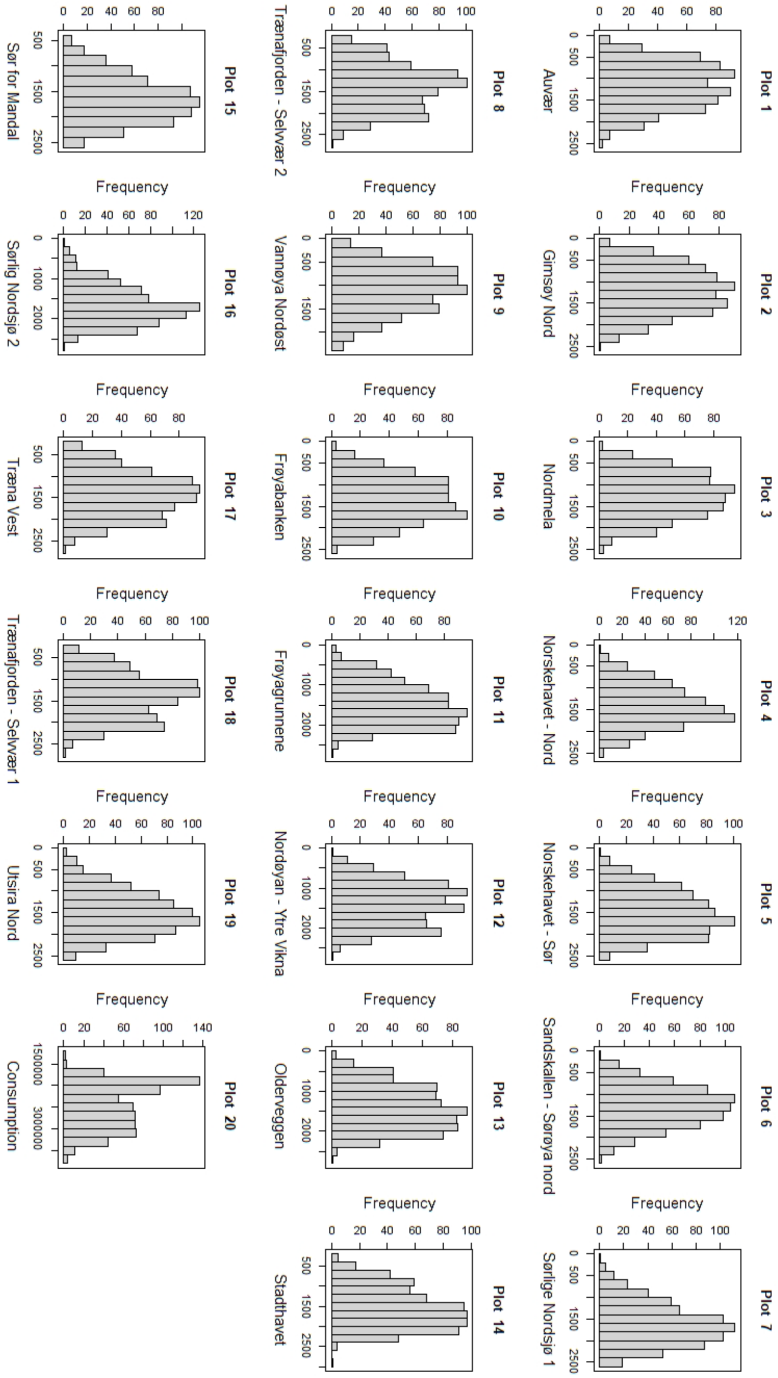

Figure A1.2: Correlation between weekly aggregated production and consumption

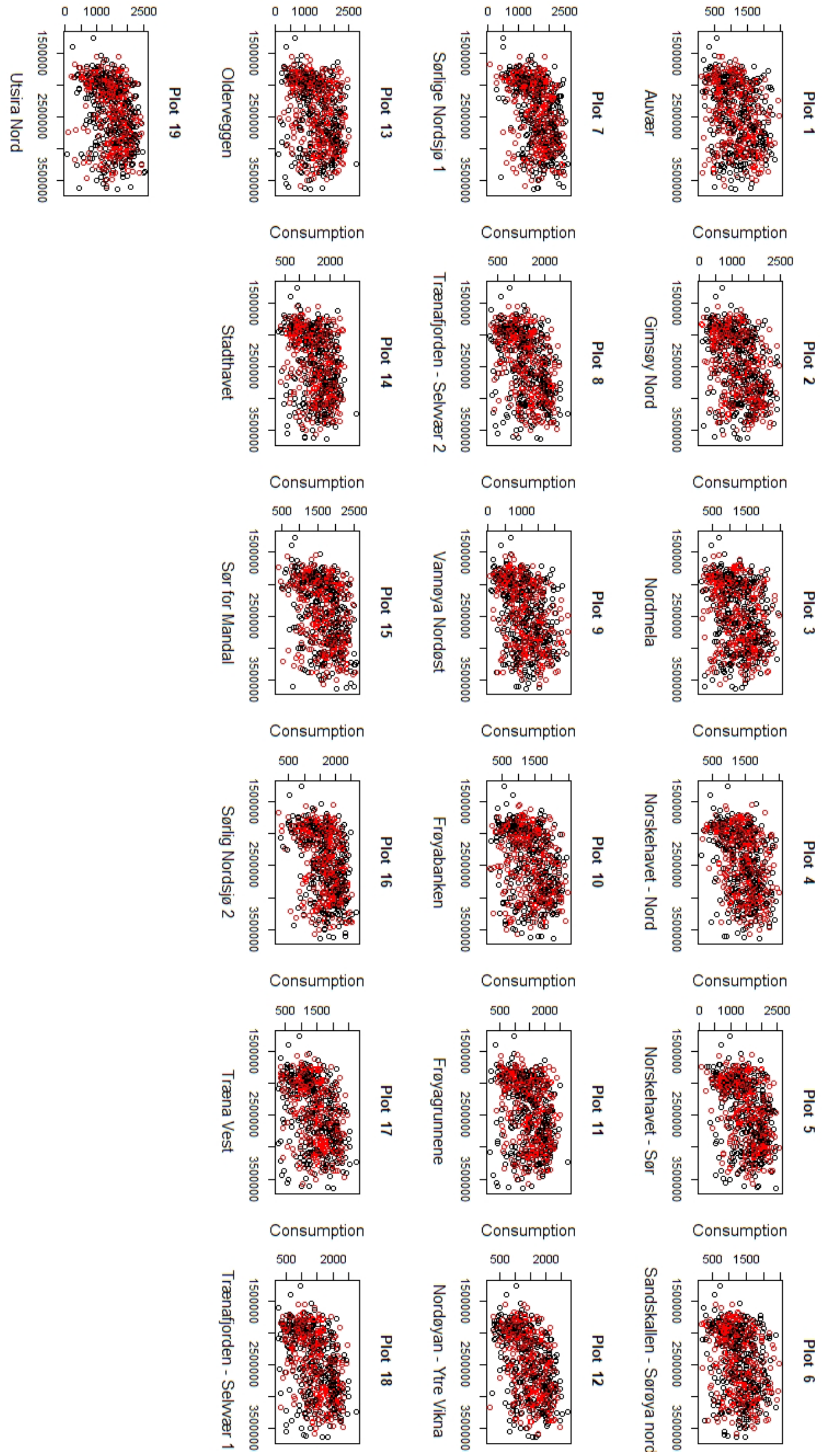

Figure A1.3: Average hourly production per month

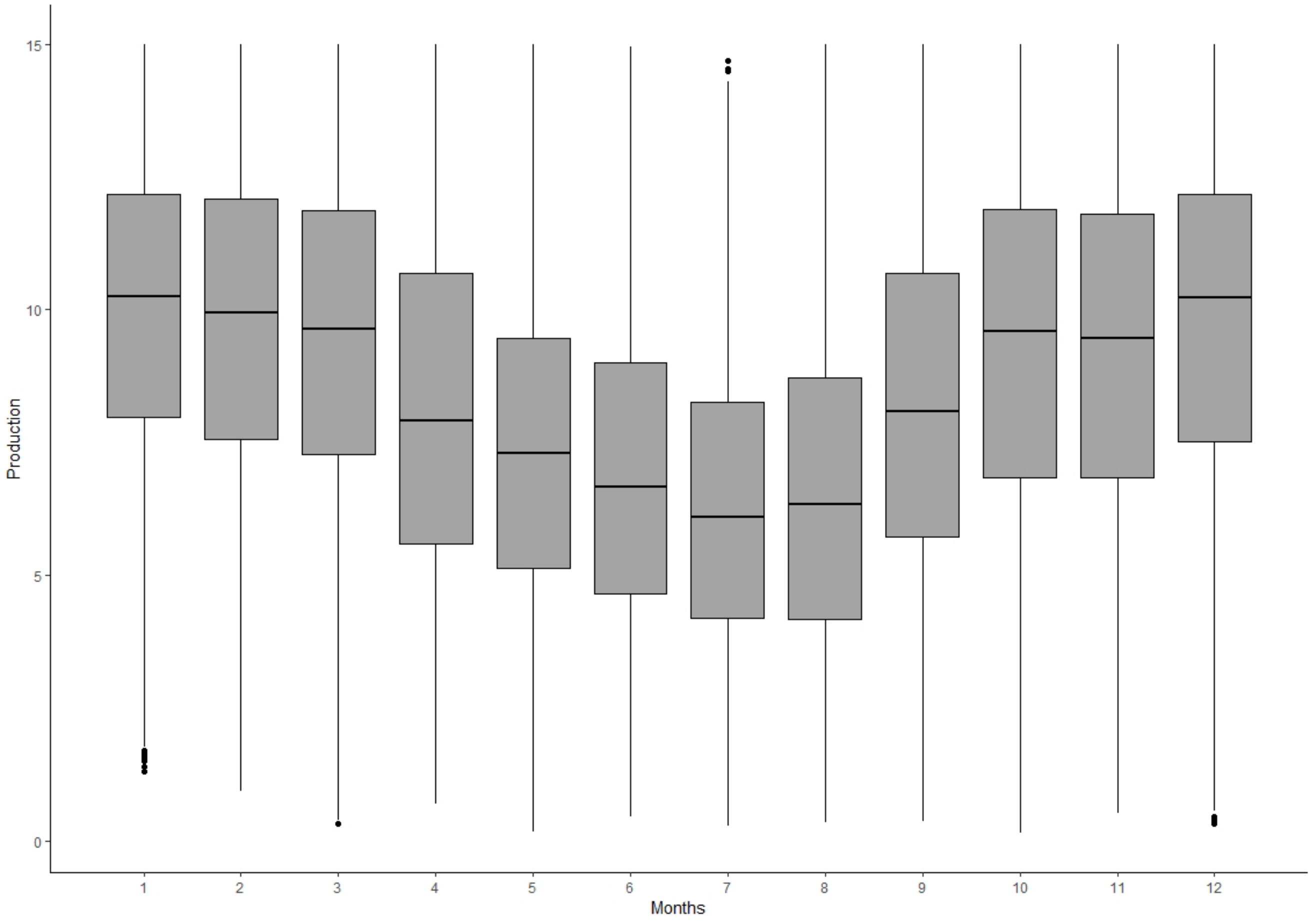

Figure A1.4: Count of hourly production, all locations

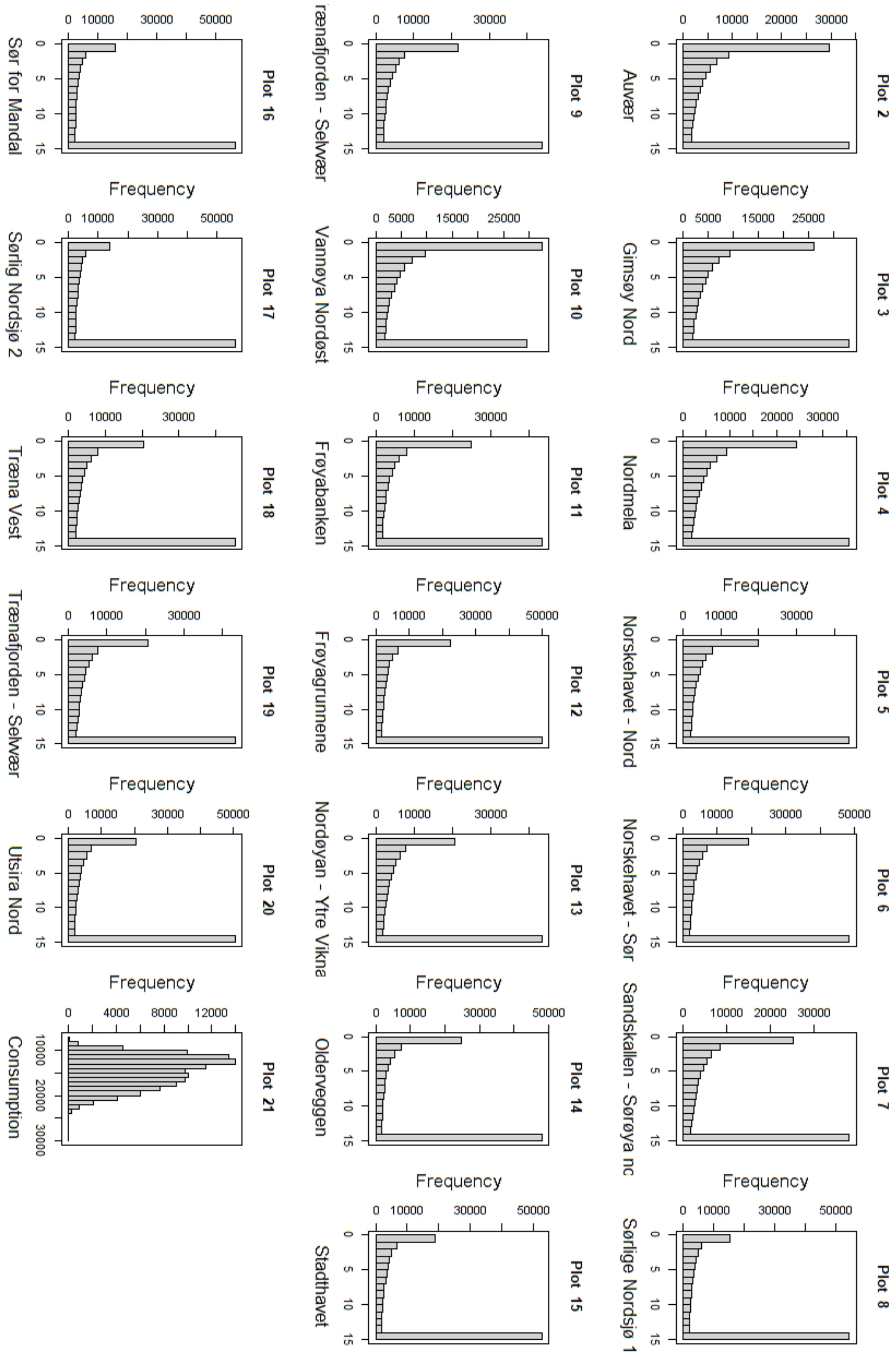

Figure A1.5: Hourly production, all locations