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Variability of renewable electricity generation in a future climate scenario

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Contents

1 Introduction

1.1 Background and motivation

Modern society is highly dependent on energy, and especially on electricity. The digitalized world needs electricity to supply power to devices and appliances. Moreover, industry also demands energy to power the production of different goods and services. The global warming and the climate change, have raised concern on the sustainability aspects of the energy production. The greenhouse-emissive fuels, such as the fossil fuels, have advancing effect on the climate change, yet those have been the primary source of energy. Growing concern with climate change has initiated an energy transition towards more environmentally sustainable renewable energy alternatives such as wind and solar power. The weather dependant, i.e. non-dispatchable energy alternatives are called the variable renewable energy (VRE). In some consideration, the VRE includes the hydro power, but in the scope of this study, the VRE is considered to consist solely of wind power and solar power.

The sustainability of energy production has been a hot topic in both national and international politics. There are both local and global initiatives and agreements restricting the use of high greenhouse emission alternatives and thus advancing the sustainable production. For example, the European Council, which is the highest political organ in the European Union, agreed to increase the renewable energy production up to 32% of the total need by 2030 [1]. The EU directive being legally binding, forces the member countries to truly take initiative and invest on the renewable alternative.

As the VRE alternatives are usually highly dependent on the prevailing weather conditions, e.g., the wind power is directly dependent on the the local wind conditions. Thus, the production is also dependent on the weather. Moreover, the production of many renewable energy alternatives is highly uneven, as the weather conditions might temporarily be favorable, causing high production, but on the other hand, timely the production is close to zero. Furthermore, the generation of renewable energy is generally difficult to control, as if the production is high, it is not efficient to reduce the production and if the production is low, there are generally no artificial ways to boost the production. Hence, by concentrating the production on the renewable energy sources, the uncertainty in the total production increases. The increasing uncertainty poses a challenge to secure sufficient production at all times, so that the energy system is able to serve all connected parties.

Due to high uncertainty in the production, the prediction to the production is difficult. Combining the uncertainty in production with the uncertainty in demand, is as difficult to predict and might even correlate with the unfavorable weather conditions, i.e., in case of cold weather there might be very low wind availability due to high-pressure areas and yet high demand for heating. There is a chance that the demand is not met with the production. Usually, this is not a severe problem, as the energy shortfalls can be compensated by buying energy from the energy markets. Yet, if the energy production is more widely dependent on the weather and the weather conditions are unfavorable also in other parts of the power grid, then there is a chance for underproduction, which could cause the power grid to collapse and cause unavailability of energy. The underproduction events are called shortfalls. The shortfalls can be considered either with respect to the production ability, i.e., the production capacities, or with respect to the total demand.

Due to the climate change, the estimation of the future weather conditions is increasingly more difficult, as the climate change increases uncertainty related to weather conditions, both locally and globally. This has a direct effect on the uncertainty in the renewable energy production.

The threat of underproduction is real as there are recent examples on situations where continental weather conditions have had a widespread effect on the production in power grid. For in January 2021, the European energy grid almost collapsed due to local underproduction in Eastern Europe [2].

Ensuring the performance and reliability of the power system is critical for functioning society motivates the need to consider the effect of variable renewable energy sources. An easy solution would be to maintain some easily controllable, i.e, dispatchable, reserve electricity production capacity, such as gas turbines. Yet, dispatchable alternatives are often greenhouse emission-intensive, which is in conflict with the goals of reducing the emissions and enforcing sustainability. This motivates the consideration of how much controllable capacity there should to prepare for situations where the production is low compared to the demand.

1.2 Objectives

The goal of this work is to research the shortfall events as an phenomenon and examine the prevalence of the shortfall events in a future climate scenario. The scope of the work is to consider the frequency, i.e., probability and the magnitude of the shortfall event.

Moreover, the shortfalls being fairly emerging phenomenon, related to possibly coming energy transition, an important goal is to contribute to clarifying the shortfalls as phenomena and produce methods to examine the effect based on given future climate scenarios. This part could be called sense-making, as it is mainly clarifying the aspects involved to shortfalls and to produce tractable metrics and visualizations of the shortfalls in different scenarios. The sense-making using the visualizations and other metrics aims to produce a simple explanatory analysis, which could be provided to decision makers who consider, e.g., security of supply or production capacity investments. The focus is on the Finnish energy production system.

In this work, shortfalls are considered by generating both production and demand data in a future climate scenario. Moreover, it is assumed that the energy markets are only internal, i.e., that there is no possibility to buy foreign supply. The future climate scenario is chosen to be a SSP2-4.5 scenario. The SSP2-4.5 scenario is a so called middle-road scenario related to the climate change mitigation globally. [3] The future climate scenario is modelled with a model which is part of the Coupled Model Intercomparison Project 6 (CMIP6) by the World Climate Research Program. The model is a Earth System Model (ESM) version 1.2 by Max Planck Institute (MPI) with low resolution. The model can be abbreviated as MPI-ESM1.2-LR, but in this work, the LR is omitted. [4] The data set is considered on the time period spanning on year 2015 to 2035. The data and the prevailing mode is described in more detail in Chapter 3

From the future climate scenario, a selection of weather-related variables is used to convert the climate model into a production estimate for the VRE sources. In relation to the VRE alternatives, also the other production methods are considered in the production. The total production of the non-VRE alternatives are estimated using the European Commission (EUCO) estimate of the evolution of the production capacities [5].

To analyze the shortfall, the production must be considered with respect to some demand. The demand data must hence be generated in relation with the estimated production. In this study, demand data is generated by repeating a five year demand cycle and adding a trend to the data using the EUCO demand evolution estimates [5]. The generation of demand is further presented in Chapter 3.3.

Using the production and demand data, the shortfall data is generated as difference of the two respectively. The shortfall data is used to analyze the frequency, magnitude of the shortfalls and conversely the needed capacities for covering the demand, considering the merit order market model related to production methods. The shortfalls are also compared with respect to difference production location to highlight and analyze the spatial effect in shortfalls. Finally, the shortfalls are analyzes in couple of simple production system scenarios.

2 Literature Review

2.1 Electricity markets

Electricity differs from other energy in that it cannot be directly stored efficiently as, i.e., the fossil fuels. However, recent developments in the electricity industry have led to the deployment of storage possibilities, such as large-scale batteries or other reserves that are filled during a low-demand period and drained upon high demand.[6] Despite recent developments, battery systems are the costly and limited in capacity. The capacity of battery systems is not sufficient for nation-scale storage. [7] In Nordic countries, hydro power reservoirs can also be seen as an alternative for electricity storage. [8]

The power generation and consumption must be balanced all the time.[9] If the balance is not achieved, the frequency of the power grid will alter. If the frequency changes too much or too rapidly, it may harm electric appliances connected to the grid. Therefore, it is vital to maintain the balance between generation and demand at all times.[10] The disturbances in the balance of the power grids is also one of the primary threats in related to shortfalls.

Before 2000s, the electricity markets were widely regulated by governmental parties, which led to a stable and predictable market. Later on, the markets have been widely deregulated, which has led to more uncertainties in the electricity prices. [9]

The system based on supply and demand has also resulted in a new way of determining electricity prices. The electricity demand is highly price inelastic, which means that an increase of the price does not have a significant effect on the demand. However, the way the price of electricity is determined is more complex. For low-demand situations, i.e., in cases where the production is notably larger than demand, the cheapest base production technologies are utilized. The actual price of electricity in the market is determined by the supply of the production methods in a way that the next cheapest technologies not yet utilized are not economically sensible. [9]

When the demand peaks, the more responsive technologies, i.e. dispatchable technologies, are generally taken in to use. For example gas turbines are generally considered dispatchable since the startup times are very short. Yet, the dispatchable technologies, tend to have a larger marginal cost resulting in higher price in the market. [9]

In Finland, the base production has historically consisted of mainly nuclear, hydro and combined heat and power (CHP) technologies. The production price of nuclear and CHP have been the lowest of any non-renewables, which implies that the technologies are the most economically attractive to use as a base production. [11]

The increasing penetration of renewable production technologies has its effects in the market. Since the renewable technologies come with nearly zero marginal cost, the usage of the technologies is highly beneficial. However, the variability of the renewable technologies poses challenges. Because the supply depends on the weather conditions, the production is also relatively uncontrollable. Therefore, the change towards more renewable intensive grids has come with its challenges and changes to the earlier market conventions. [12] Moreover, grids with high VRE penetration are expected to behave in a different way, because the price levels can be hard to state and storage power can become a relevant factor in production mix. [13]

2.2 Energy policies

To mitigate climate change, there has been a variety of international and national agreements. The Kyoto Protocol, being the first initiative towards global goals to limit the climate change, is the basis of climate change mitigation policies. It was agreed on in 1997 and entered into force in 2005. [14]

After the Kyoto Protocol, the European Union published a low-carbon roadmap in 2011. The goal is to reduce emissions by 80% by 2050 in comparison to the 1990 level of emission. For 2030, this roadmap aims at reducing emissions by 40%, similarly in comparison to the 1990 levels. The roadmap also introduced a 2030 roadmap and further development strategies to be done. [15] This roadmap has been a base for studies on the feasibility of a low-emitting European electricity system.

In 2015, a new climate change mitigation policy, the Paris Agreement was signed. The Paris Agreement aims at limiting the global average temperature rise below 2 degrees, preferably below 1.5 degrees Celsius in comparison to the pre-industrial times. This goal is achieved by setting nationally determined contributions (NDC). The process is then tracked by using an enhanced transparency framework. Following the introduction of the Paris Agreement, many countries have introduced low-carbon plans and even zero-carbon solutions. To support the NDCs, Paris Agreement offers both technological and financial support for the member countries. [16]

Because the NDCs differ throughout the globe and the scope of this work is in Finnish electricity system, it suffices to consider the European and Finnish NDCs. For the EU, the Paris Agreement has had a remarkable role in cutting emissions. The so called European Green Deal was launched in 2019 to drive the actions.

The total emissions, in comparison with the level of 1990, have already been cut by 22% and the aim is to cut at least 55% of all emissions by 2030. Moreover, the European emissions trading system (EU-ETS) was introduced in 2005. The EU-ETS aims to set caps and tender out the emission rights in the EU states. [17] The European NDC results in a stricter mitigation policy than introduced earlier with the low-carbon roadmap.

All in all, the energy sector is responsible for 75% of all EU's greenhouse gas emissions. Therefore, the energy sector is the most significant industry in EU's emissions. Thus, the Green Deal will have a massive impact on it. Actions to decrease the emissions in EU come with two perspectives. On one hand, the energy efficiency is attempted to be enhanced, and on the other hand, the emission footprint of the power generation is decreased. The current work in EU concentrates on integrating and building an EU-wide energy infrastructure and investing in renewable energy sources, especially offshore. [17] The latest EU-level agreement concerning the climate change mitigation is the EU Renewable energy directive, which legally binds the members states to increase the share of renewable energy sources up to 32 % of the total demand by 2030 [1].

The impacts of EU's climate and energy targets have been estimated with different scenarios. The most recent of such estimates is the EUCO3232.5, which is a scenario where the EU-level renewable gross production share is increased to 32% and an efficiency target of 32.5% is achieved. The scenario reflects on how the 2030 targets can be achieved. For the Finnish capacity portfolio this means a significant decrease in coal-powered energy production capacity and similarly, a notable increase in wind and gas capacities. [5]

2.3 Modelling renewable energy production

As the VRE sources depend on the weather conditions or other conditions, which are not controllable, the control of the generation level is also limited. This has an effect on the large-scale integration of the VRE technologies in energy systems. Capacity expansion models are utilized to model the effect of such integrations. The capacity expansion models are generally large-scale optimization models that are used to minimize either total costs or backup capacity.[18]

In order to estimate the production of the VRE sources, one needs to be able to transform the climate data, i.e. the weather conditions to power output.

2.3.1 Wind power conversion

Wind power modelling poses many challenges ranging from the site selection to the lay-out optimization. All these problems require defining the power conversion from prevailing wind conditions to power output. The variety of methods for estimating the wind power output is vast. Cranmer et al. [19] determines the wind power output from a reference curve for a 5 MW reference turbine. On the other hand, Nuno et al. [20] also account the power output dynamics of the wind turbines, which are obtained by geographical smoothing. Furthermore, van der Wiel et al. [21] introduce a method where they first convert wind speeds to the height of a turbine and then with a roughness parameter convert the wind speed into capacity factors. The capacity factor is determined using a truncated third power curve, which deviates from zero is a cut-in speed is achieved. Then, the power is determined by scaled third power function depending on the rated wind and the cut-in wind. When the rated wind, i.e., in speed after which the production output no longer increases, the output is one. Yet, if the wind speed is too high, the turbine is stopped. This is determined by the cut-off speed, above which wind speed the capacity factor is zero because the turbine needs to be protected from the torque by the wind. In this work, the methods suggested by van der Wiel et al. [21] are used. The method is more accurately described in Chapter 3.2.2.

2.3.2 Solar PV conversion

The methods for estimating the power output of the solar PV are numerous. There are more degrees of freedom related to the solar PV generation. E.g., as the moving sun affects the radiation, i.e., the direction of sunlight, and thus that of the solar radiation, differs by the time of day. These kind of effects need approximations.

In the comprehensive framework for estimating the future scenarios by Mattson et al. [22], the solar PV is generated by separately considering the power generation by the direct sun light, and two diffuse components from ground and from air. All in all, this model considers the dependence from the angle of incidence related to setting of the solar panel. Another method for generating the solar PV output presented by Nuno et al., who infer the power output as a weighted average over an ensemble of different scenarios regionally [20]. A third method is presented by van der Wiel et al. [21], where the solar PV output is determined from the downward flux by determining a power output factor for the solar PV cell with respect to regulated test temperature. This is obtained by considering the temperature change of the PV cell, which is the greatest factor affecting the power output besides the downward flux. For the ease of use and tractability, this methods is selected for this work. This methods is presented in more detail in Chapter 3.2.2

2.4 Energy demand

Energy demand is cyclic on daily bases and highly dependant on the prevailing weather conditions. E.g, if the temperature outdoors is low, the buildings tend to use more energy, and also electricity, in order to heat the buildings. On the other hand, if the temperature is high, there is a need to cool down the building. This behavior can also be inferred from the data as Miragedis et al. suggests [23]. Moreover, while electricity demand is highly cyclic due to the daily routines of people, challenges arise for meeting demand at all times. To achieve the balance, controllable production is required.

The demand of electricity is not only weather dependant but also related to technological development. Yet, the concern for climate change and potential savings in costs have driven initiatives for energy efficiency. Due to the changes in energy efficiency, despite the possible technological development, the electricity demand might not increase. Yet, the evolution of the demand is dependent on the area of consideration, as found in study by Boßmann et al. [24]. It has been estimated that global energy demand will increase by 11%-27% by the year 2050 due to the effects of climate change. [25] This further amplifies the difficulty of estimating the future scenarios. Furthermore, the possible growing number of electric cars has a significant effect on the demand. The demand not only changes in the magnitude in the future, but the technological development affect other aspects as well. The demand is expected to become more controllable and flexible due to future developments in smart grid technologies which would make the challenging combination of cyclic and weather dependent demand and weather dependent VRE easier to adapt to. [12] [26]

Thus, because demand depends on many uncertain aspects, it is not only methodologically difficult to estimate. The methodological difficulties in estimation of the future are also due to the increasing variance in predictions for future conditions. Moreover, from the modelling point of view, the estimation of the effect of potential technological advancements is difficult. In this work, the speculation with technological advancements is not considered explicitly. The demand estimation is based on estimates by the European Commission in a technical report related to the renewable energy directive [5].

In the literature, there are variety of ways to model the energy demand. Usually, the demand data is generated by using historical data as a baseline. E.g., Turner et al., the estimate demands based on a model that uses demand from major population areas to estimate the future demand based on estimated energy efficiency and demand growth estimates. [27] On the other hand, energy demand has been modelled also by using logistic regression models in the case of van der

Wiel. [21] According to Boßmann et al. [24], in the literature, most demand generation methods tend to use simple scaling methods for historical data. Boßmann et al. suggest that is is in general not suitable for long term demand estimates, due to changes in markets. In this work, the demand generation is conducted by using historical data to obtain the general annual trend of demand. The historical data is then scaled according to the estimated evolution of demand obtained form EUCO report [5].

2.5 Electricity shortfalls

The shortfall phenomenon, is related to weather conditions. The effect of meteorological conditions on variable renewable energy generation has been studied by, for example, van der Viel et al. Specifically, local and even continent-wide weather conditions, such as wind-drought and cold winters pose a serious threat to the power grid. [21] There has also been research on impacts of climate change on smaller scale, such as on a power plant level. According to Turner et al., the research on power grid scale is lacking. [27]

The energy grids should also be considered on more local level, as considering, e.g., country's ability to meet the demand is a concern of security of supply. Moreover, the weather conditions can vary locally. In this work, the Finnish power generation ability in the future scenario is considered. Finland is a long country spanning on over 1000 kilometer are in longitudinal direction. The spanning causes high variation of weather conditions within the same country. Whereas the southern regions experience high wind availability, there might be, e.g., a strong low-pressure are on northern regions affecting the weather conditions differently. This motivates the consideration of spatial effect of energy generation.

A similar research considering the same renewable energy alternatives has been conducted on Germany's Exclusive Economic Zone by Kaspar et al. [28], the photo-voltaic (PV) and wind energy were found to have a complementing seasonal cycle. In the paper, an even distribution of installed capacity was assumed. The shortfalls were considered in a sense of capacity threshold, which resulted notably long shortfall periods. Adequacy of production has been considered, and especially wind power production, as the solar PV production is not usually profitable in many location. In a paper by Levin et al., a capacity expansion model is built to examine the shortfalls with respect to wind power share in the production mix. In the paper by Levin et al., the revenue is also considered, which is often omitted in the considerations. [29]

In recent research, there has been efforts to build sophisticated decision support systems considering the shortfall events. Frank et al. [30] consider balancing the potential of wind and PV energy generation across European countries. On the other hand, Mattson et al. [22] suggest a method for automatic generation of renewable energy supply curves, hourly capacity factors and synthetic electricity demand for arbitrary region. Despite being very comprehensive, the model is very computationally intensive, requiring extensive amounts of memory and computational capacity. Thus, e.g., for the use of this work, the model is unusable due to the complexity. This motivates a need for a light-weight model being able to convert climate model data into production data, in order to clarify the shortfall phenomenon to decision makers without extensive investments to model of the complexity of one suggested by Mattson et al. [22].

The methods used to capture shortfalls are often two-fold, on one side, the capacity factors are considered to exhibit the shortfall phenomenon, as in paper by Kaspar et al. [28]. On the other hand, the other consideration is the availability of enough supply to meet the demand, which is considered, e.g., by van der Wiel et al. [21] These two methods are also used to quantify the shortfall in this work.

2.6 Future climate scenarios

Estimating and predicting the energy production and demand is highly depends on future scenarios. Especially, in the case of future renewable energy estimation, the future weather conditions have significant effect. Usually, authors tend to use different models for predicting the future climate scenarios. The papers tend to describe accurately the parametrizations and the data sets used. The differences between different modes are in the modelling decisions. Most climate models are physical models describing the earth system with different set of modelling restrictions. The models are constantly developing. Yet, due to CMIP6 and other organizations, there are some standardized scenarios for future circumstances, which can be shared among models. An example of these are the Shared Socio-economic Pathways, SSPs. The scenarios are used to fix, e.g, the temperature evolution in a scenario. E.g in the model by Mattson [22], the SSPs are used to extend data to future scenarios.

In this work, the model for future climate is given by the Earth System Model (ESM) by Max Planck Institute (MPI). [4]. The model is a contribution to the CMIP6 project, which is a project maintaining a set of standards and historical data for the models. [31] A detailed description of the CMIP6 scenarios is given in the summary paper by O'Neill et al. [32]

3 Data and methods

To investigate the shortfall phenomenon in an energy system, the shortfall data must to be generated. In the most intuitive manner, the shortfall can be understood as pointwise underproduction. In this work, the production related shortfall is understood as the magnitude of underproduction, i.e., the shortfall $S(t)$ at time t is given as

$$S(t) = \begin{cases} 0, & P(t) > D(t) \\ |P(t) - D(t)|, & D(t) > P(t) \end{cases} \tag{1}$$

where $P(t)$ is the production at time t and $D(t)$ is the demand at time t. Thus, the shortfalls are the absolute value of the difference in production and demand, whenever the demand exceeds the production. Hence, the shortfall data is obtained by first generating the power demand data and power production data.

On the other hand, one needs to infer an energy market model, to combine the production and the demand in the sense of which alternatives are used and when. Moreover, since we are investigating the shortfall events occurring in future, the production and demand data must be estimated from suitable data that is available.

The production data is generated utilizing the output of CMIP6 project model, MPI-ESM-LR [4] output from a SSP245 scenario. Furthermore, the production data is scaled by utilizing the production capacities for Finnish power grid. The capacities are estimated by the European Commission (EUCO) in their technical review [5]. On the other hand, the demand data is generated by using historical data from Finnish energy consumption. The data is obtained from Fingrid [33]. The data is then scaled to match the demand trend estimated in the EUCO technical review.

3.1 Future climate data

In this work, the future climate data is obtained from an instance from the Earth System Model, version 1.2, by the Max Planck Institute (MPI-ESM1.2). More specifically, the low resolution version MPI-ESM1.2-LR is used. The difference between the different resolution version of the model is the used simulation grid. In the low resolution model, the grid is coarse, with approximate grid spacing of 200 km. The MPI-ESM1.2-LR model is part of international collaboration called Coupled Model Intercomparison Project phase 6 (CMIP6). The CMIP6 is an entity coordinating and designing climate model experiments. The goal of the work of CMIP6 is i.a. to support and coordinate separate climate models for intercomparability and standards for e.g., scenarios. [34], [31] The benefit of the low resolution model instance is that it computationally efficient and requires little storage. Yet, the weakness is that the model has relatively low resolution, resulting to approximately 200km grid spacing. [4]

More specifically, the data from the model is from SSP2-4.5 scenario. The SSP (Shared Socio-economic Pathway), scenarios are a standard way to represent the socio-economic development during the time span of the model. The SSP scenarios also include the Representative Concentration Pathway (RCP) scenario, describing the development of greenhouse gas emission during the time span of the simulation. The SSP-RPC combinations are usually written such that the first part announces the SSP scenario and the latter the RPC scenario. In the case of this work, the data is from SSP2, RCP 4.5 scenario. The SSP2-4.5 scenario is a 'middle-road' scenario, the sosio-techno-economic trend does not change markedly, the development remains uneven and environmental systems degrade although the is some improvement. The RCP 4.5 scenario corresponds to a scenario, where the greenhouse gas mitigation efforts are existing but not very comprehensive.[3]

The selected data set contains data from model instance 'r1i1p1f1', which is one of the initial condition variants. The data set selected contains data from the first of January 2015 03.00, until 00.00 on January 1st 2035. The data is obtained from the data node hosted by German Climate Computing Center (DKRX). [35] For the purpose of this work, only four variables from the model output are obtained. The variables are the air temperature (tas), the surface downward shortwave flux in air (rsds) and the north and east components of the wind speed (uas, vas). All the variables are determined with three-hour interval, meaning that there are observations from every third hour.

The data is obtained from the model output from 10 separate location. As the grid of the MPI-ESM1.2 model is with approximately 200 km spacing, the grid points from the model do not represent the selected locations accurately, but the simulation output of the closest grid point. The selected location and the corresponding grid points are presented in Figure 1.

Figure 1: The selected location of consideration marked as blue dots and the corresponding simulation grid points with red dots. All the location are connected to nearest grid points, which is illustrated with black line.

The locations were selected to reflect the current of future production areas of the wind and solar PV energy. Some sites, like Kajaani and Jyväskylä were selected to obtain reasonable coverage over the whole potential production area in Finland.

The Figure 1 shows, that the selection of locations is not perfect as the in the simulation model do not completely match the selected locations. Yet, the selected location are justified as the goal of the project is to build understanding of the phenomenon, not produce accurate estimates. Note, that as the Figure 1 shows, the selected locations Pori and Nauvo are actually projected to the same simulation grid point. Thus, this will result in perfect correlation of results in further consideration of these two locations.

3.1.1 Wind speed data

The wind speed data is a simulation output calculated 10 m above mean surface level. From the two wind speed components, the wind speed data is obtained by omitting the wind direction and computing the wind speed as length of the sum vector wind speed, i.e. as

$$v = \sqrt{uas^2 + vas^2} \tag{2}$$

The wind speed forms the time series presented in Figure 2.

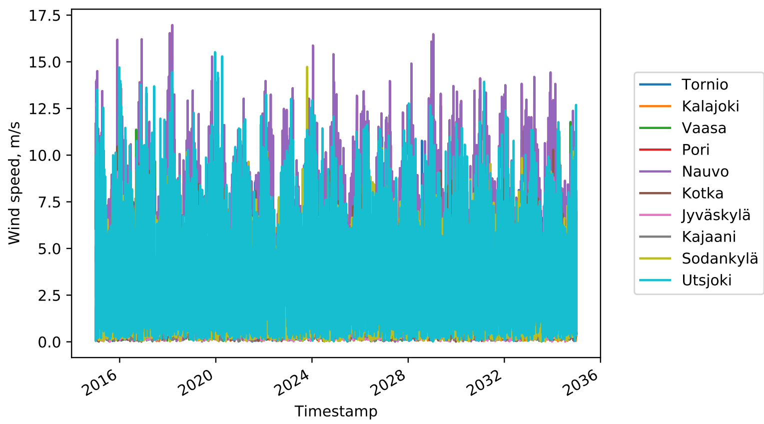

Figure 2: The time-series of the wind speed data calculated from the uas and vas variables using Equation (2). The data contains wind speeds from all the selected ten locations.

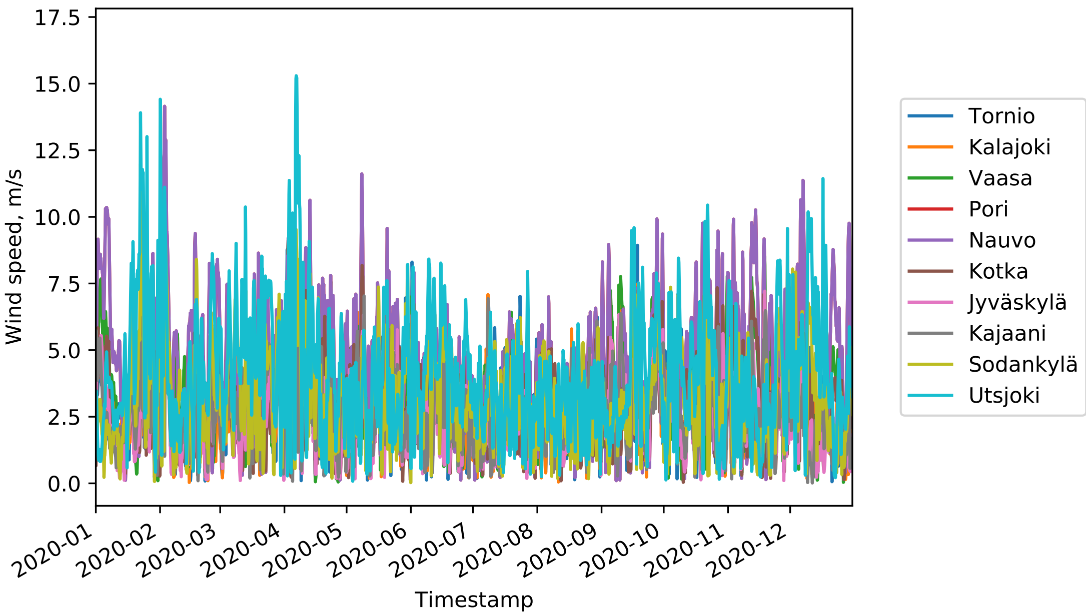

Figure 3: One-year period of the raw wind speed data in all the ten locations of consideration.

The wind speed data in Figure 2, exhibits realistic behavior. There are some clear peak wind speeds, which are approximately 15 m/s, which corresponds high, almost storm wind speeds. Yet, as the data is in a sense an average of three hours, there are no extremely high gust winds, which are only temporally. Because time series is 20-years long, it is difficult to observe the more delicate variation of the wind speed in Figure 3. In order to depict this, a one-year span of the data is presented in Figure 3.

From Figure 3, the prevaling wind speeds can be easily observed. On average, the wind speed seems to be fluctuating between almost zero and about 5 - 7 m/s in most of the locations. The Figure 3 also shows that actually, the strongest wind speeds are observed in Utsjoki location, in the Northern Finland. Yet, observing the data more closely, one can see that usually, the wind speeds are highest in the Nauvo, as the corresponding color is most often as highest peak. It is also notable, that there are no long periods of zero wind speed in any location, which suggests that the data captures the high fluctuation of the wind speed.

3.1.2 Solar radiation data

The raw solar data from the MPI-ESM1.2 model describes the downward flux of the shortwave radiation from the sun, i.e., the power per area that the solar radiates on short waves to the atmosphere. Note, that the variable is indeed the downward flux, as the most common direction of the flux is downwards. Yet, the data contains short periods, where this value is negative. This corresponds to the events where the sky might be very clear and the net radiation is actually upwards in the atmosphere. These values are truncated to zero, as the data is used for energy production estimation and the upward net flux does not contribute to loss of energy in the production system. The raw, untruncated data is presented in Figure 4.

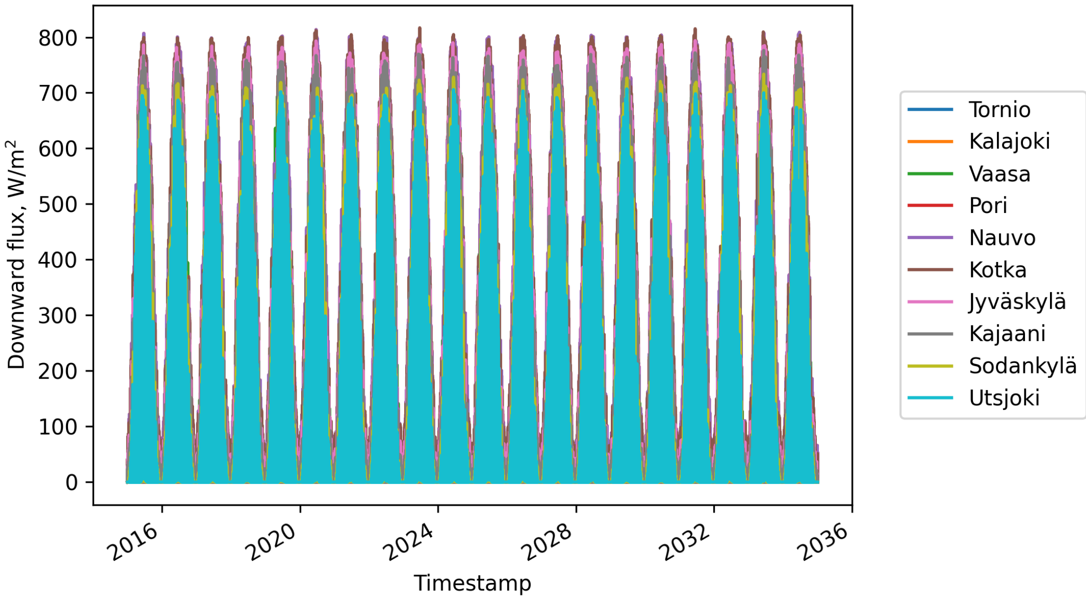

Figure 4: The downward flux of short wave solar radiation during years 2015-2035, in the MPI-ESM1.2 simulation output from all the ten locations.

Figure 4 depicts the downward flux of the short wave solar radiation during the year 2015-2035. The data is regular with a yearly cycle, which is expected. Thus, this suggests that the data well captures the true variation of the solar radiation. Figure 5 presents a one-year part of the whole data.

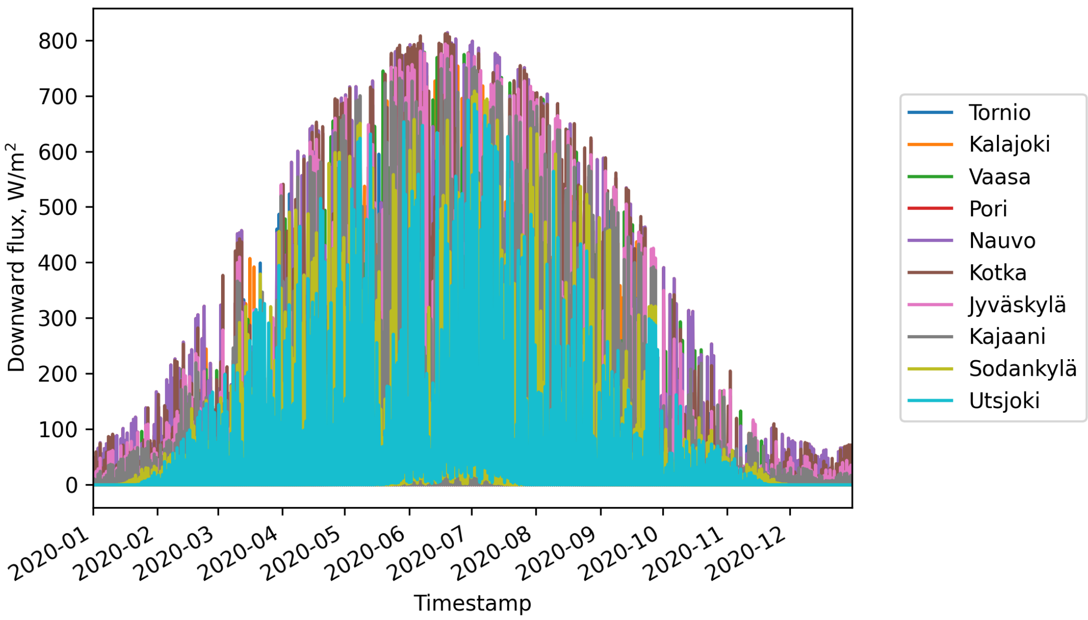

Figure 5: One-year period of the downward flux of short wave solar radiation from the MPI-ESM1.2 simulation output in all the ten locations.

From the Figure 5 the yearly variation of the solar radiation is even more clear than from the Figure 4. Now, the one-year data not only confirms the yearly fluctuation, but also implies other real-world phenomena. By looking the data, one finds that in Utsjoki, which is located in the most Northern parts of Finland, the solar radiation is non-zero during the summer time and on the other hand zero during the winter time. The data also shows that the most Southern location has always the highest flux, which is well in accordance with the known behavior that the close to the equator the location is, the more solar radiation in the location. With these observations, one can deduce that the data seems to well capture the real-world phenomena related to weather, which supports using the data in the estimation of the VRE alternatives, which are highly dependent on the weather conditions.

3.1.3 Temperature data

The last variable from the MPI-EMS1.2 model is temperature data, which is needed in determination of production capacity factor of solar PV power. This data is simulated for the air temperature at height of 2 m. The data is presented in Figure 6.

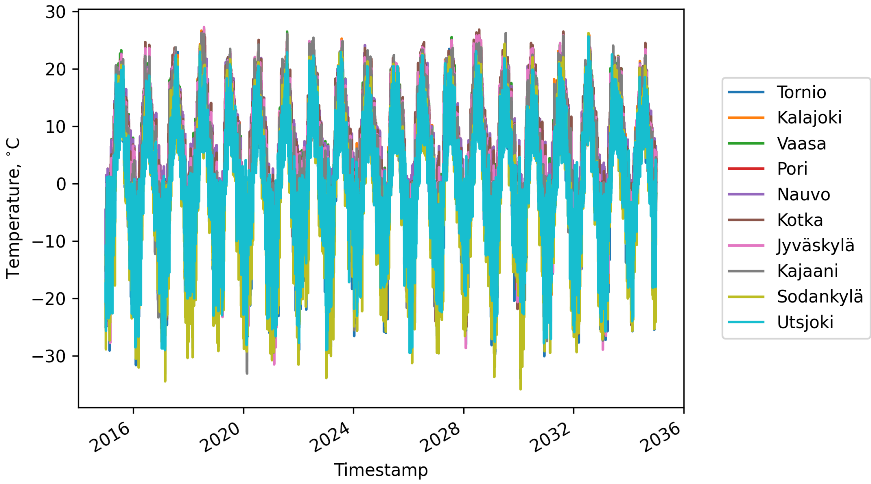

Figure 6: A closer look at the solar flux data as obtained by CMIP6.

The annual variation of the temperature data is well observed in the Figure 6. Moreover, the data also, in this case, captures the real-world phenomena rather well. One sees that in a Northern inland location, such as Sodankylä, the lowest temperatures and on the other hand the highest temperatures do not differ that significantly. To illustrate this more accurately, a one-year period of the data is presented in Figure 7.

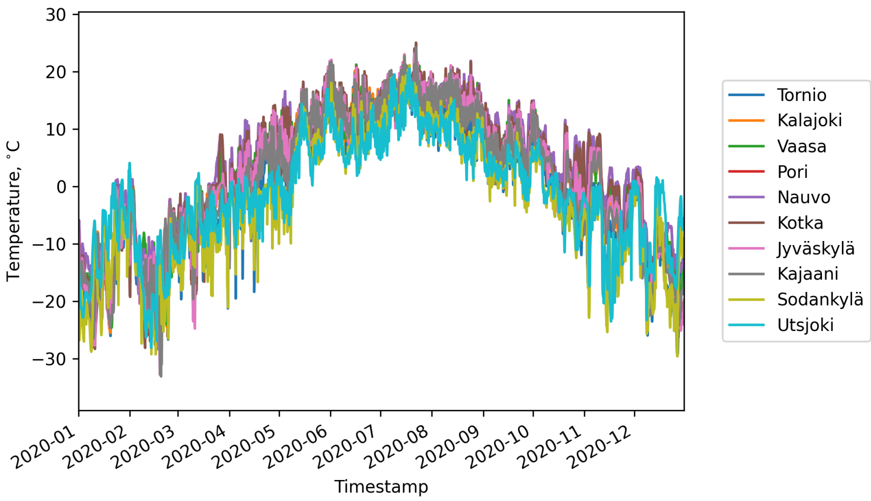

Figure 7: The downward shortwave radiation data from the MPI-ESM1.2 model from year 2015-2035.

The one-year in Figure 7 confirms the observations made from the whole temperature data. Yet, it seems that the inland locations are warmer. This phenomenon can be observed in reality. Thus, the data seems to rather well represent the real-life setting.

The timestamps of the temperature data differ from the ones in other variables. The offset of the timestamps is 1 hour and 30 minutes. This issue is omitted because the temperature is considered only in relation to the temperature of the PV cell. The 1.5 hour delay is therefore interpreted as a lag in the temperature change of the PV cell and the timestamps are assumed to be in accordance with the wind and solar data timestamps.

3.2 Generation of production data

To consider shortfalls, one needs to determine the capacity factors of the production methods. The capacity factors also help considering the shortfalls with respect to the total production, which is the more intuitive form, in addition to considering shortfalls as events of low capacity factors.

This Chapter, first presents generation of the production data and then the generated production data is analyzed and validated qualitatively.

3.2.1 Production capacities

Production of electricity roughly divides in three main categories: the VRE, having notable varying production, the baseload, that runs evenly all the time, and the dispatchable technologies, that are generally controllable to meet the demand. In this work, some of the baseload and dispatchable categories are understood to be similar.

The baseload and dispatchable categories, in the Finnish production system, are nuclear power, hydro power, biomass power and other combustion technologies such as gas, coal and peat. In general, nuclear power represents the ideal form of baseload and therefore nuclear power is considered as an individual technology. Moreover, hydro power can, in most cases, also be utilized as a reserving capacity and therefore help making the production more flexible. Therefore, the hydro power is also separated from the other alternatives, since this would allow to analyse the reservoir feature of hydro power in further studies.

The remaining production technologies form a combustion power category. The combustion power includes mostly dispatchable technologies even though some technologies, such as coal, can be considered baseload. However, in this study, all the other combustion power methods are considered as if those were dispatchable since the proportion of baseload capacities is low and in some cases it can be challenging to separate dispatchable technologies from baseload technologies.

The production categories used in this study are therefore solar PV, wind power, nuclear power, hydro power and other combustion methods. The capacities of these production methods are assumed to follow estimates in the EUCO report [5]. The estimates are presented below in Table 1.

Table 1: Net generation capacities in Finland as stated by the European Commission [5].

Category	**Method**	**Capacity (MW) for years** 2015-2020	2020-2025	2025-2030	2030-2035
VRE	Wind power	1 001	2 456	4 159	4 516
	Solar PV	12	9	9	19
	VRE total	1 013	2 465	4 168	4 545
Nuclear	Nuclear	2 726	4 378	4 378	3 398
Hydro power	Hydro power	3 276	3 276	3 371	3 511
Combustion	Gas	2 698	2 819	3 730	3 593
	Biomass	2 589	2 791	2 812	3 495
	Solids	4 340	3 303	1 681	1 274
	Oil	1 532	643	637	617
	Combustion total	11 158	9 556	8 861	8 979

The estimated production capacities in Table 1 reflect the EUCO climate change mitigation efforts. The energy transition is observed especially from the manyfold investments to wind power. Moreover, the dispatchable gas power capacity investments are notable. On the other hand, decrease in solids and oil capacities reflect the diminishing use of fossil fuels. The data also takes account the evolution of nuclear capacity in Finland. The earlier investments to nuclear power realize in the beginning of 2020s and on the other hand, some of the older power plants come to an end of their life cycle by the end of 2035, which is accounted in the estimates.

3.2.2 Converting capacity to production estimates

To find the production estimates, the net production capacities presented in Table 1 must be multiplied with prevailing production utilization shares, called capacity factors. In this work, the combustion technologies and nuclear and hydro power are assumed to withhold capacity factor of one, meaning that the total net capacity can be fully utilized. In reality the capacity factors are neither constant nor necessarily close to one either, but for the sake of simplicity, this is omitted in the work. On the other hand, as the weather conditions affecting the VRE capacities change, the capacity factors also change. Thus, the VRE capacity factors require more accurate consideration.

3.2.3 Wind power capacity factors

For wind power generation conversion, the method suggested by van der Wiel et al. [21] is utilized. The method suggests that the wind power output capacity factor deviated from the zero only if the wind speed on the height of the wind turbine hub exceeds certain cut-in speed, v_{ci}. Once the cut-in speed is exceeded, the production is assumed to follow a third power curve until a certain wind speed, called rated wind, v_r, is reached. The rated wind is a wind speed after which the wind turbine is able to generate maximal output and can no longer benefit from higher wind speeds. During the wind speeds exceeding the rated wind, the capacity factor is one. Yet, at very high wind speeds, the wind turbine cannot produce energy due to danger of the turbine failing due to the high torques. This effect is accounted by setting a upper limit, i.e., the cut-off speed for the wind turbine. Whenever the wind speeds exceed this limit, the turbine is shut down and the capacity factor falls to zero.

Because the production is dependent of the wind at hub height and the simulation output is from the height of 10 m, the wind speeds need to be scaled to match the wind speeds at given height h. Van der Wiel et al. suggest using a power law with a roughness parameter describing the effect of roughness of the land. The power law can be formulated and parametrized as follows: the wind speed at height h at time t

$$V(h,t) = V(h_0,t)\left[\frac{h}{h_0}\right]^{\alpha}, \tag{3}$$

where h_0 is the reference height of 10 m and α is the roughness parameter. In this work, the wind turbines are assumed to have height of 150 m and a roughness parameter value of $\alpha = 0.143$, which according to van der Wiel et al. [21] corresponds to on-shore production, i.e., wind power production on land by the water areas. For the inland locations this estimate is hence upper limit, as the inland land masses create even more friction than the shore areas.

Having obtained the wind-at-height, the wind energy potential, i.e., the capacity factors W_{pot} are obtained as

$$W_{pot}(t) = \begin{cases} 0, & \text{if} \quad V(t) < V_{ci} \\ \frac{V(h,t)^3 - V_{ci}^3}{V_r^3 - V_{ci}^3}, & \text{if} \quad V_{ci} \leq V(t) < V_r \\ 1, & \text{if} \quad V_r \leq V(t) < V_{co} \\ 0, & \text{if} \quad V_{co} \leq V(t), \end{cases}, \tag{4}$$

where V_{ci} describes the wind cut-in speed, V_r the rated wind speed for turbine specific maximum production and V_{co} wind cut-out speed.

Based on the capacity factors, the total production is obtained by multiplying the capacity factors of the wind power production with corresponding capacities presented in Table 1, the total production of wind power is obtained. The time evolution of a evenly distributed capacity is presented in Figure 8 for each location separately and for the total production of wind power, i.e., the sum of all separate locations in Figure 9.

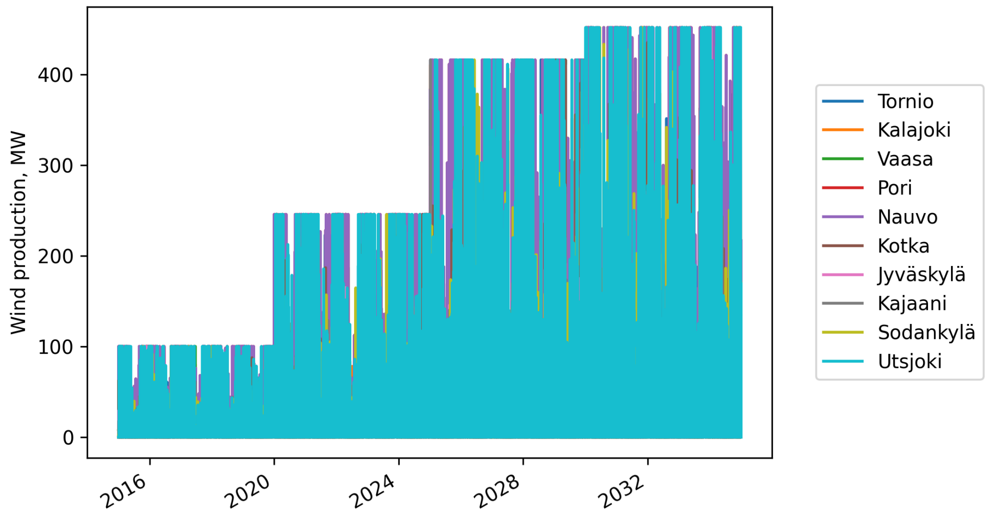

Figure 8: The time evolution of the wind production with a capacity portfolio, where the total capacity is divided evenly to all location.

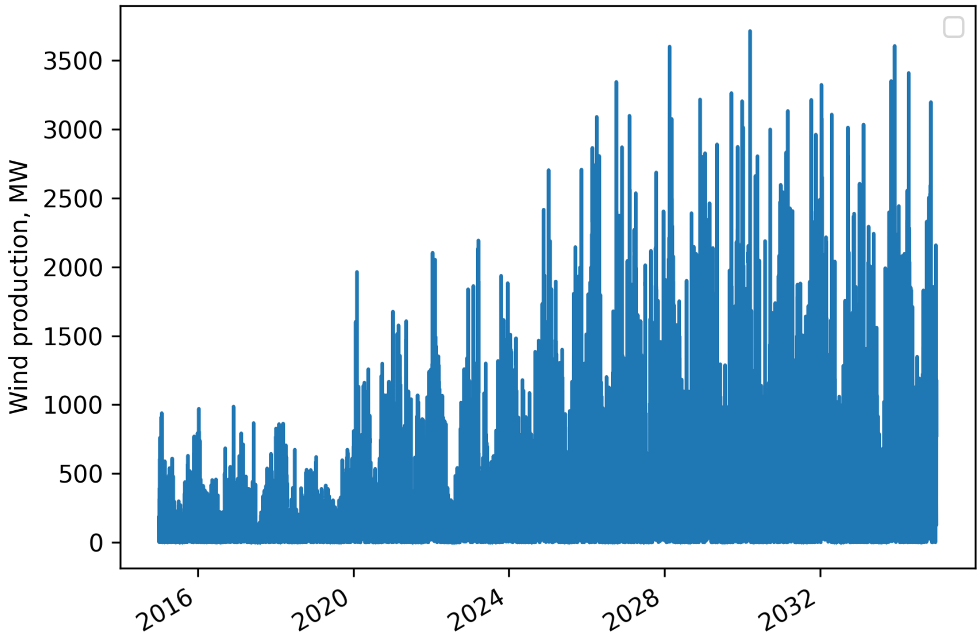

Figure 9: The time evolution of the total wind power production, where the total capacity is divided evenly to all location.

Figure 8 shows the separate amounts of generated power for each location. Figure 8 clearly shows that the production often runs at the full capacity. Yet, it is worth a mention that in the figures describing the whole time series, the line width of plots amplifies the separate spikes due to non-zero widths of a line in pixels. Figure 8 also shows that there are many situations, where the wind production is not running at full capacity. These events seem to become more frequent in the long run.

Figure 9 presents the total production. Figure 9 shows that actually the investments to wind power, which are seen in Table 1 increase the total production notably. Yet, it seems that the same effect of low production events becoming more frequent in the latter parts of the time series is shown as lower values for production on the low points of production in about year 2032-2035. All in all, the total supply of the wind power is approximately 2000 MW/h by the 2028. Before that the production is lower but it is worth to mention that in this time the energy transition is yet in process so there is notable amount of combustion power alternative in use to cover the demand.

3.2.4 Solar power capacity factors

The solar PV generation is estimated as suggested by van der Wiel et al.[21]. In this work, the parametrization of the solar PV generation is set equal to the parametrization presented in the paper by van der Wiel et al.[21].

The solar PV potential, i.e., the capacity factors are determined by first scaling the downward flux of solar radiation with a constant value determined to describe the standard test conditions. The standard condition flux value has been determined to be 1000 W/m^2. Then, the scaled flux is multiplied with a power factor, $P_r(t)$, which describes the performance of the PV cell. The power factor, $P_r(t)$ is determined as follows

$$P_r(t) = 1 + \gamma[T_{\text{cell}} - T_{\text{ref}}], \tag{5}$$

where $\gamma = -0.005$ is a constant describing the negative effect of temperature on the performance of the PV cell. $T_{\text{ref}} = 25°\text{C}$ is a constant temperature in which the PV cell performance is measured and T_{cell} is the temperature of the PV cell.

The temperature of the PV cell T_{cell} is a combination of mean day temperature of air, $T_{\text{a, day}}$, the solar radiation, $G(t)$ and the wind speed V(t). The mean day temperature of air in calculated as

$$T_{\text{a, day}}(t) = \frac{T_{\text{a, mean}}(t) + T_{\text{a, max}}(t)}{2},$$

where $T_{\text{a, mean}}$ is the mean of the temperature and $T_{\text{a, max}}$ is the maximum temperature. The needed temperatures can easily be calculated from the data available.

Thus, the formula for temperature of the PV cell can be written as

$$T_{\text{cell}} = c_1 + c_2 T_{\text{a, day}}(t) + c_3 G(t) + c_4 V(t), \tag{6}$$

where c_i are constants. The values of the constants where set to following values: $c_1 = 4.3°\text{C}$, 0.943,0.028 m$^2/W$, and $c_4 = 1.538°\text{Cs/m}$.

By determining the capacity factors using the equation 5 and multiplying the capacity factors with corresponding capacities presented in Table 1, the solar PV production is obtained. The solar PV production for each location is presented in Figure 10 and the total solar production, i.e., the sum of different locations, is presented on Figure 11.

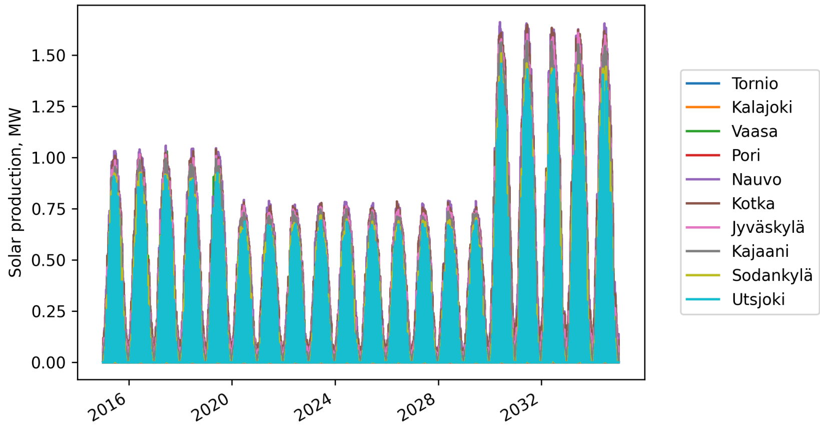

Figure 10: The time evolution of the solar PV production for each of the separate locations.

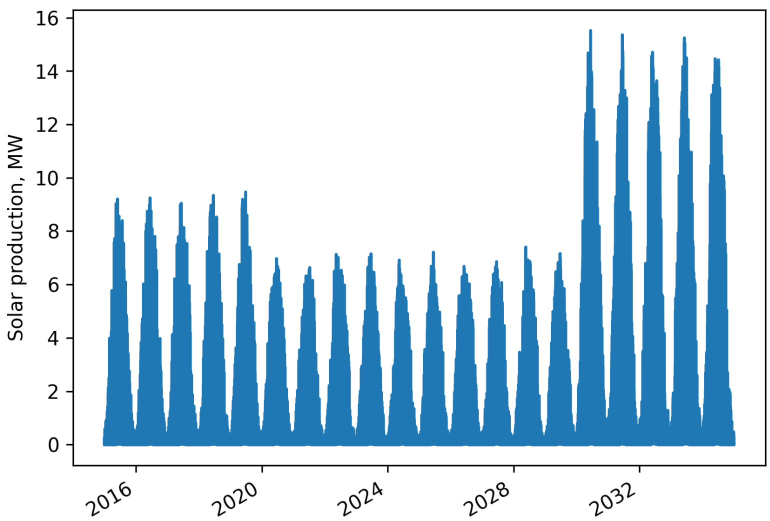

Figure 11: The time evolution of the total solar PV production.

Figure 10 shows that the variation of solar production by location is quite small. Yet, the data reflects the longitudinal position of the production sites. The key observation is that with the Finnish capacities, the solar PV production is almost non-existing. By comparing the total solar PV production presented in Figure 11 with the total wind power production, one notices that the wind power production is 200-fold compared to the solar PV production. Thus, with the estimated capacities, the solar PV production in Finland is not meaningful in the scale of the total production system.

3.3 Generation of demand data

In general, the demand data can be assumed to consist of two components, the trend and a fluctuating component. The trend depicts the evolution of demand, where as the fluctuating component accounts for the smaller scale changes. The demand data is generated by using historical data by Fingrid [33] as the fluctuating component and the future demand evolution estimates according to the EUCO3232.5 scenario [5] as the long-term trend.

The Fingrid demand data represents a real Finnish consumption from the start of the year 2015 to the end of the year 2019. The 5-year cycle is appended with a scaled 5-year period until the end of the year 2034. Utilizing historical data in demand estimation is a method found in the literature as seen in the Chapter 2.4. However, in literature, the factors such as temperature and population growth are considered as external variables. In this work the estimate for average demand from EUCO is utilized as a scaling factor,i.e., the trend. The trend scaling is conducted based on the year 2015, for which the scaling value equals to 1. The Fingrid historical demand data is provided on hourly basis but it is matched to the production data by utilizing only every third hour. Using the presented methods for demand data generation results in to demand that is presented in Figure 12.

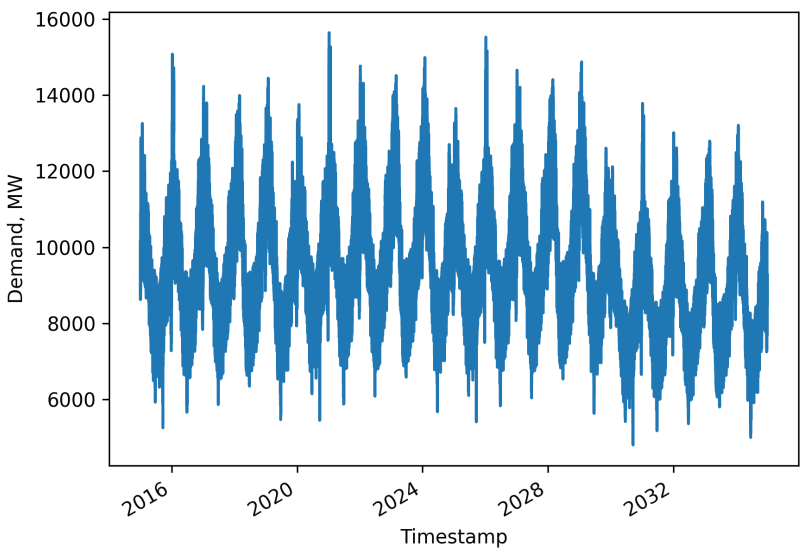

Figure 12: The generated demand data.

The demand data in Figure 12 illustrates how the overall demand first increases and then decreases after 2030. Moreover, the 5-year cycle highlights some events every fifth year which can be seen as peaks and repeating characteristics of the demand. Even though the data might include some extreme cases, it represents events that can happen time to time. For the purposes of this work, a demand estimate as such describes the phenomenon adequately. However, that the events caused by the cyclic nature of the demand data aim to broadly describe the phenomenon rather than provide detailed estimate on the future demand.

3.4 Model of the energy market

To form a more realistic way of combining the demand and production values, a merit order model is combined to the production of energy. The merit order models describe the utilization of the production such that the marginally cheapest methods are utilized first and if more production is required to fulfill the demand, the following production alternative is used. The model in this work is an approximation based on model of conventional markets suggested by Ekholm and Virasjoki [13].

In this work, the VRE technologies represent the cheapest method, as the production marginal cost is assumed to be almost zero. Thus, the VRE is always utilized first. The second alternative is nuclear power, since it is a baseload technology with a relatively low marginal costs. Third segment is the hydro power, since even though it runs with low marginal costs, the reservoir feature, can be easier utilized and hence it is meaningful to utilize this alternative before the dispatchable alternative. This study does not cover the effects of reservoirs but the idea is presented as a base for further studies. Finally, last alternative in the merit order is the other combustion capacities which will form the dispatchable power.

The idea of the merit order model is graphically described in Figure 13. The Figure 13 illustrates scenario at certain time t, where the demand level is met with just a slight usage of combustion power. Theoretically, the price level would be determined according to the combustion technologies, but in this work, the exact price is omitted and only the ordinal rank of alternatives matters.

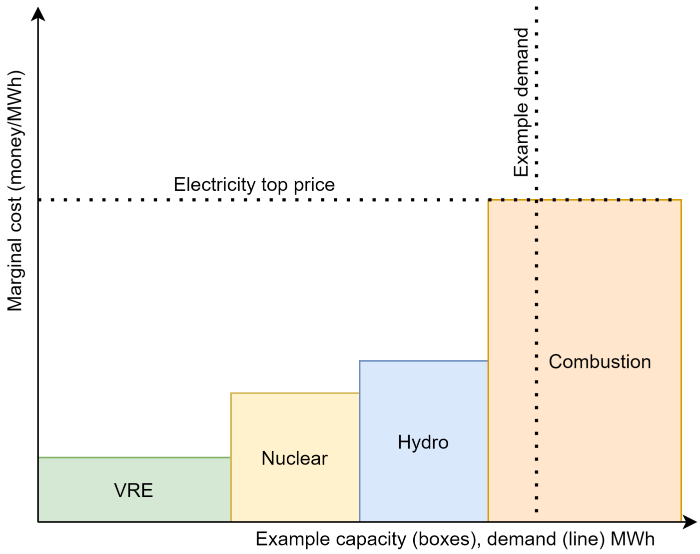

Figure 13: A simple merit order illustration representing the utilization of production.

Based on the merit order market model, the load and demand are matched. Figure 14 illustrates the utilization all available production capacity is utilized between 2015 and 2034. The Figure 14 shows the total availability of production with respect to the demand illustrated with a black line. The demand represents the balance of the technologies in case of a demand.

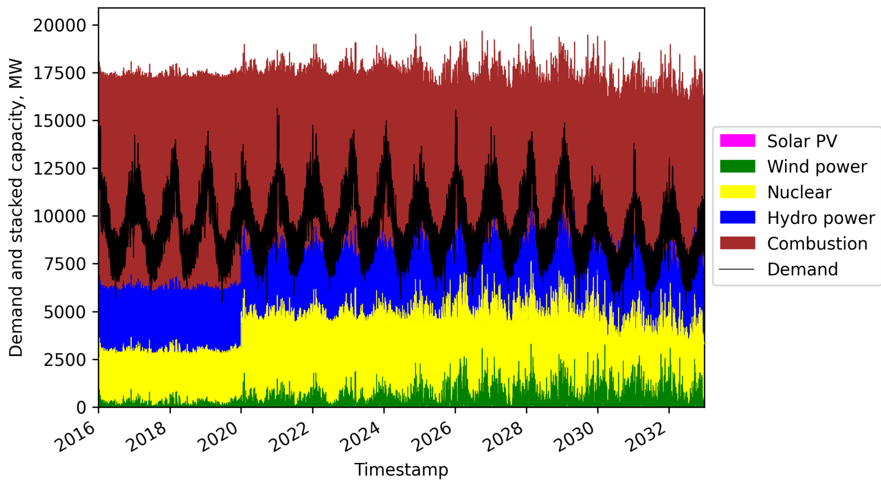

Figure 14: Stacked available production in a case where VRE capacities are distributed evenly between the locations.

Figure 14 shows how the demand is usually smaller than the available total production. In Figure 14, the solar PV production is not visible due to the small capacities. Figure 14 also illustrates the increasing capacity of VRE production after the year 2025 starts to increase the variability the total available production level heavily.

4 Analysis and results

In this Chapter, the shortfall data generated in Chapter 3 is analyzed. First, the shortfall data is analyzed for each location separately. Based on these results, a selection of portfolios, i.e., combination of locations, is constructed for further analysis, as the effects of shortfalls are more interesting in portfolios which reasonably accounts for the effect of spatial distribution of production. For each of the formed portfolios, the shortfall events are analyzed. First, an introductory analysis is conducted, then the shortfall data is examined with respect both total production and capacity factor related definitions of the shortfall.

4.1 Analysis of the individual locations

4.1.1 Wind production

First, the Figure 15 presents the annual averages of the capacity factors of wind power production with respect to all production location.

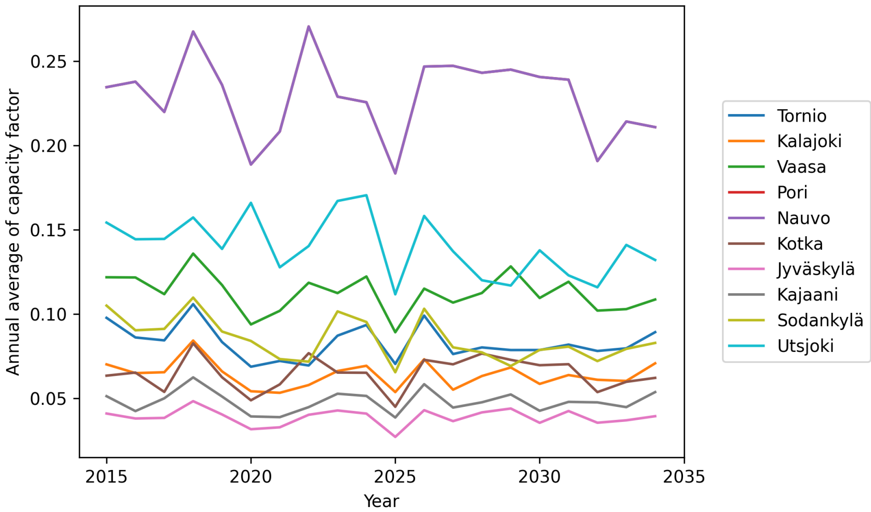

Figure 15: Annual average of wind power capacity factor between years 2015 and 2035.

The capacity factors in Figure 15 imply that Nauvo and Pori, having identical capacity factor profiles, produce the most electricity in comparison with other locations. Both of these locations generate on average 23% of the maximum capacity. Moreover, Utsjoki and Vaasa are relatively productive, as Utsjoki has average capacity factor of 14% and Vaasa 11% . The least favorable, in terms of average capacity factors, are Jyväskylä and Kajaani, which both average in 3-5% of installed capacity. The low availability of wind power in Jyväskylä and Kajaani is expected as the location are deep in the inland. On the other hand, Nauvo, Pori and Vaasa are coastal locations in the Western Finland, which allows expecting high wind power availability. Utsjoki, which also has high average capacity factor, is located in Northern Finland, but it is fairly close the Arctic Ocean, which explains the high availability.

In order to form portfolios of the selected production sites, one should be interested of the correlations of the locations. If two locations are highly correlated, the two are probable to experience shortfalls simultaneously, which is unwanted quantity of a good portfolio. The correlations of capacity factors of the locations is shown in Figure 16.

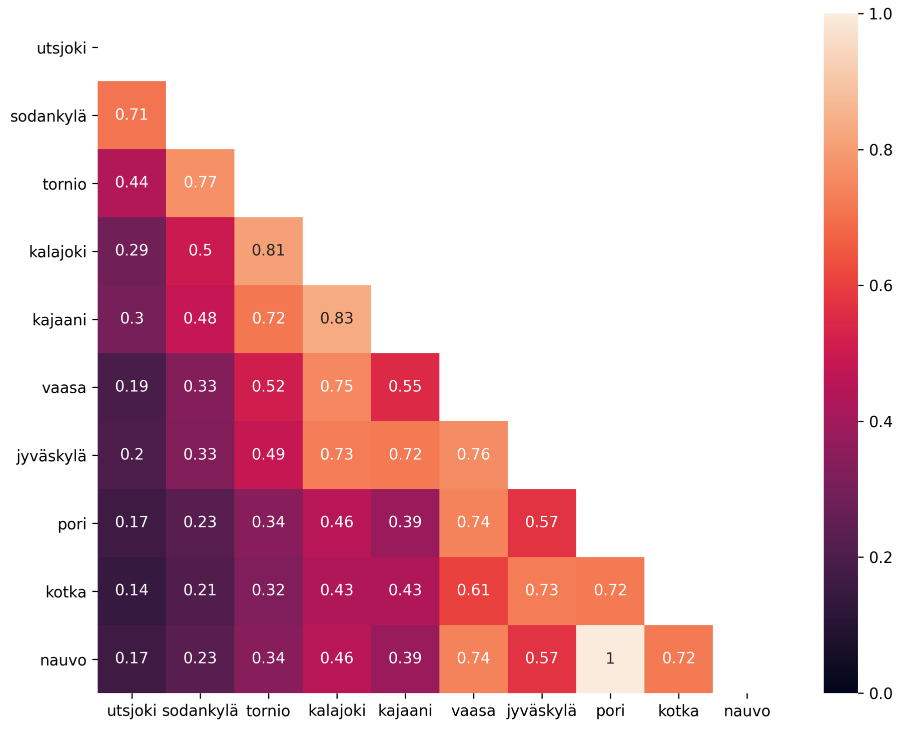

Figure 16: Wind power production factor correlation between locations.

The correlation factors in Figure 16 imply that the correlation is highly dependent on the longitudinal difference of locations. Note, that the correlation of Pori and Nauvo is exactly one. This is due to the fact that the two location have the same simulation grid point.

Given these results, the capacity of wind power production roughly depends on the distance from the coast and the correlation decreases when the longitudinal distance is increased. Therefore, the selection of best production locations should theoretically favour coastal areas.

4.2 Solar PV production

The annual averages of the solar PV capacity factors with respect to production locations are presented in Figure 17.

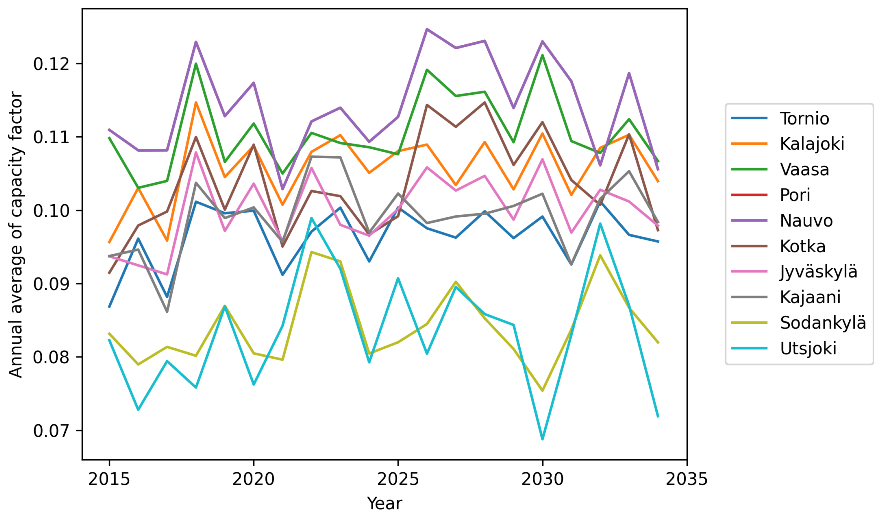

Figure 17: Annual average solar PV capacity factor between years 2015 and 2035.

All the averages vary in the range of 7% to 12% and do not deviate notably from each other. Yet, Utsjoki and Sodankylä average a lower capacity factor than the other locations. The probable explanation is the longitudinal location. A northern location reduces the availability of solar radiation as large amount of possible production hours are during the polar nights, when there is no sunlight. The rest of the locations have a relatively similar profile but in general, the more southern location, the higher capacity factor.

Figure 18 presents the solar PV capacity factor correlation between the locations.

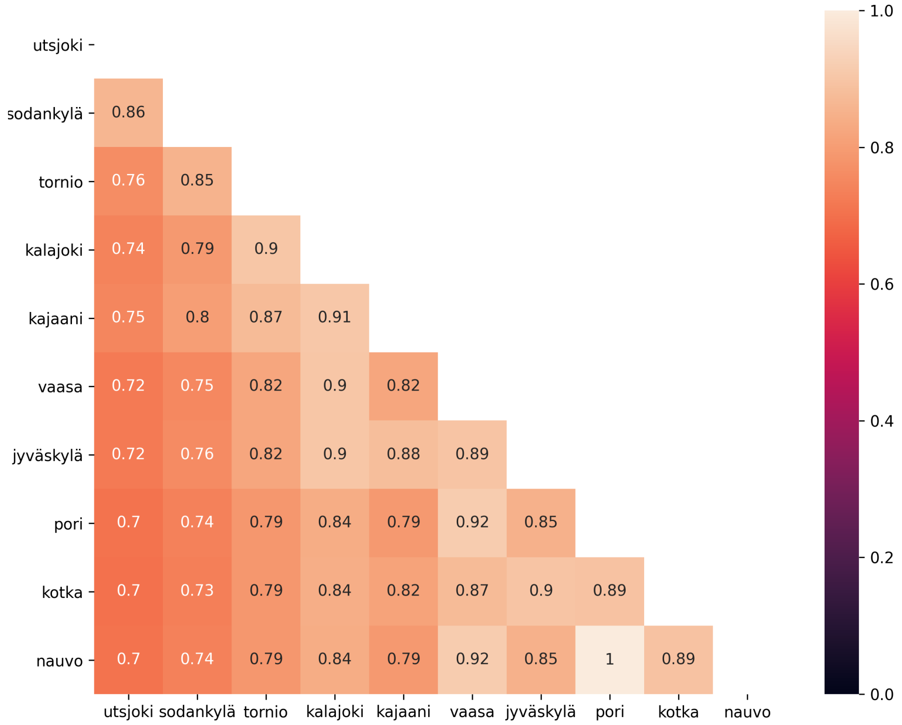

Figure 18: Solar PV production factor correlation between locations.

The correlations are relatively similar to each others, but similarly to the Figure 17, a trend of decreasing correlation with an increase in longitudinal distance is observed. A probable explanation for the result is that the solar availability is highly cyclic with both daily and annual frequencies. This results in higher correlation between all locations, as the phenomenon is almost perfectly timely correlated within the locations.

4.3 Generation of portfolios

To form a production distribution portfolio there are two main features to consider. A successful portfolio would consist of locations with high average production capacity. Moreover, a low correlation between the locations would likely to result in low correlation of shortfalls, which would be likely to maximize reliability and thus minimize the shortfall occurrences. This kind of selection of portfolios is highly greedy heuristic. In order to find truly optimal portfolio, an optimization problem would need to be formulated and solved.

The results in Chapter 4.1 imply that the correlation is mainly due to the longitudinal distance. This suggests that in order to acquire a portfolio with low-correlations, the distance between the locations should be maximized. The average capacity factors presented in Figure 15 and 17 implies that Nauvo, Pori and Utsjoki would be the most favourable locations and Jyväskylä and Kajaani the least favourable with respect to availability of production.

If the maximization of production is the most important criterion, Nauvo is the primary location for the portfolios since it has the largest average capacity factor. As Pori is exactly similar to the Nauvo due to the simulation grid points, it can be neglected from the portfolios. Together with Nauvo, Utsjoki is a opportunistic selection, for its relatively high average capacity factor and low correlation with Nauvo. As Jyväskylä is the worst location with respect to average availability of production, a portfolio containing that location is meaningful for comparison purposes. It has a low correlation with Utsjoki, the two are good choice with respect to the correlation criterion. Additionally, a case with completely equal division of production between all the sites is investigated. In this portfolio each of the ten selected locations has share of 10% of the total production. Thus, the portfolios for further analysis are presented in Table 2 with the corresponding shares of capacity.

Table 2: Average utilization of available capacities.

Number of portfolio	**Locations**	**Shares**
1	Nauvo	100%
2	Utsjoki	100%
3	Jyväskylä	100%
4	Nauvo and Utsjoki	50% each
5	Nauvo and Jyväskylä	50% each
6	All even (all 10 locations)	10% each

4.4 Utilization of capacities

In Chapter 3.4, the total capacities were adequate for production meeting demand at all times. With the portfolios defined, the effects of different spatial distribution of production is studied.

In Table 3, the average utilization level of each technology is presented. The utilization level refers to the share of production that is utilized to meet the demand. Note, that the utilization level is not same as capacity factor but the actual share of utilized production obtained by using capacity factors and capacities. For the values marked with an approximate symbol (≈) the production not always being fully utilized but it approximates to 100% is highlighted.

Table 3: Average utilization of available capacities.

Portfolio	**Utilization level**			
	VRE	Nuclear	Hydro power	Combustion
Nauvo	100%	≈ 100%	95%	20%
Utsjoki	100%	≈ 100%	97%	22%
Jyväskylä	100%	≈ 100%	99%	24%
Nauvo & Utsjoki	100%	≈ 100%	97%	21%
Nauvo & Jyväskylä	100%	≈ 100%	98%	22%
All even	100%	100%	98%	22%

Table 3 shows that the utilization level of combustion capacity is a key factor. The utilization level of the combustion capacity is presented in the Figure 19.

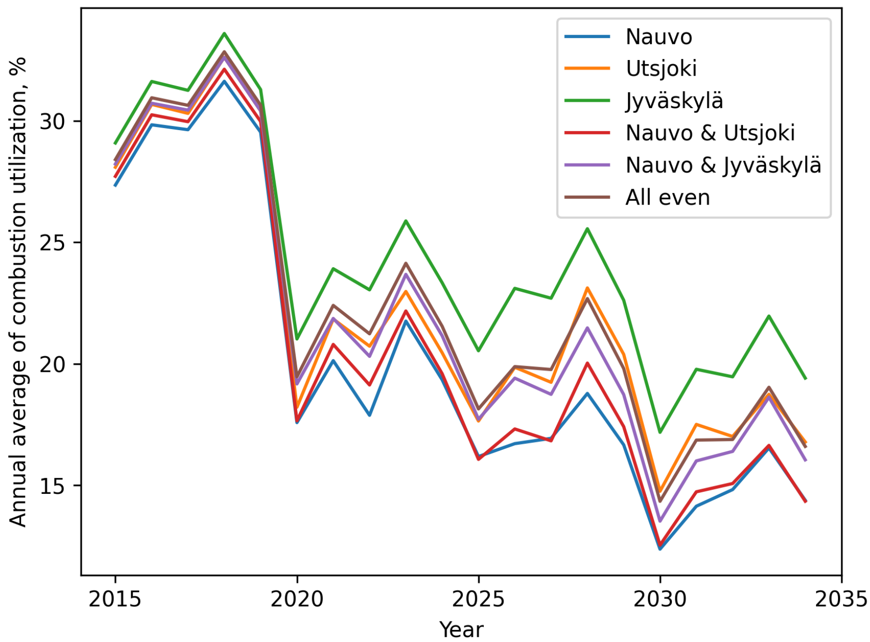

Figure 19: Annual average of combustion utilization level in the selected portfolios.

Figure 19 implies that the trend in the use of combustion is decreasing, and a drop in utilization of the combustion alternatives is clearly visible between years 2019 and 2020 as well as 2029 and 2030. The decrease is mainly due to the increasing capacities of nuclear, especially in 2019-2020, and VRE. The utilization levels between the locations vary due to varying production levels of VRE. Jyväskylä, as speculated earlier, requires the most combustion, since its low VRE capacity factors result in low total VRE production. On the other hand, Nauvo and the portfolio of Nauvo and Utsjoki are relatively similar in utilizing combustion. This suggests, that the portfolios produce a relatively equal amount of VRE on an annual level.

Another variable highlighting the difference of the portfolios is the utilization of the hydro power, which is the next production method in the merit order after the nuclear power. This suggests that in low production demand, the hydro power is the most probable alternative to be left unused. The annual average utilization of the hydro power is presented in Figure 20.

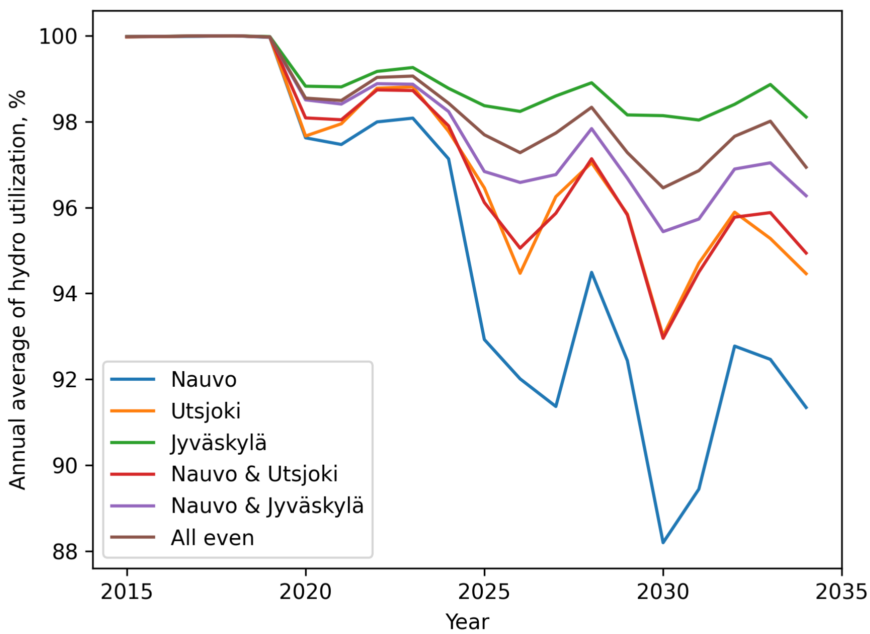

Figure 20: Annual average of hydro power utilization level in the selected portfolios.

Investigating the utilization level of hydro power in Figure 20 the increase of wind and nuclear capacities is observed. By 2020 hydro power is generally fully utilized.

Yet, After 2020, the utilization levels start to differ. By 2035, Nauvo exhibits least usage of hydro capacity suggesting that the wind power production on Nauvo is efficient in comparison to the other locations. However, Nauvo seems to require the least hydro power capacity whereas in the utilization of combustion capacity, the level was relatively similar to the portfolio consisting of Nauvo and Utsjoki. An explanation for this can be that the Nauvo portfolio averagely results in highest peaks in production with comparison to the other cases.

Considering the utilization of hydro power and combustion alternatives, Nauvo as well as the joint portfolio of Nauvo and Utsjoki seem the most optimal production portfolios. As expected, Jyväskylä and the portfolio consisting of all locations have worse performance in terms of average VRE production. However, even though Nauvo and Nauvo and Utsjoki have a relatively similar utilization level of combustion, Nauvo has clearly lower hydro power utilization. This indicates that the peak production of Nauvo and Utsjoki is lower than that of merely Nauvo.

4.5 Analysis of shortfall events in the selected portfolios

There is not only single definition for a shortfall event. The two approaches discussed in this work are the demand dependent inadequacy of production and the low availability of production, i.e., low capacity factors. According to results from Chapter 4.4, the total capacity in the Finnish electricity production system is sufficient to prevent shortfalls related to production if the production is fully utilized. However, since the electricity market considered does not allow buying or selling electricity. Neither is the price level of electricity is considered, which leads to the situation where shortfalls must be observed directly from the data. Shortfalls are considered in the view of the two definitions separately.

4.5.1 Production shortfall

Since the demand level never exceeds the maximum total production levels, the shortfall of production is considered in an alternative setting. The shortfalls are considered as if there was no combustion production available. This helps at understanding the distribution of the usage of combustion, i.e, the tail events of demand which generally causes shortfalls. The distribution of shortfalls with respect to the magnitude is presented in the Figure 21.

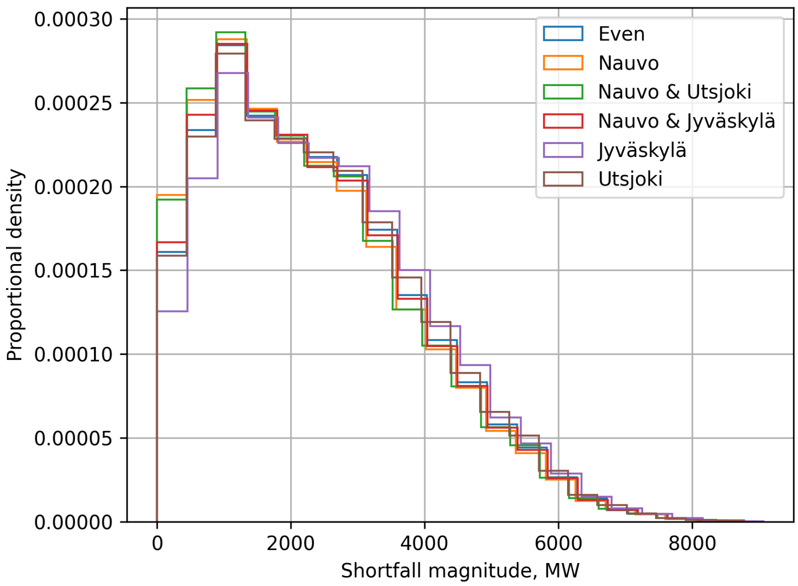

Figure 21: A Histogram describing the distribution of shortfalls without 0 valued shortfalls.

The distribution of shortfalls, shows how portfolios such as pure-Nauvo, as well as Nauvo and Utsjoki, have higher amount of shortfalls of a magnitude less than 2 000 MW. The other portfolios, such as Jyväskylä, have larger share of shortfalls of around 4 000 MW. The tail of the distribution shows that all shortfalls phase out after 8 000 MW. This is due to the demand data. As the generated demand has some maximum value, the shortfall magnitude cannot increase without a limit.

The distribution of shortfalls can also be considered in a cumulative manner. Figure 22 presents the cumulative distribution of the shortfalls with respect to the production. The cumulative distribution includes the distribution of both all shortfalls as well as cases where shortfalls do not occur, that is, the cases of zero combustion capacity.

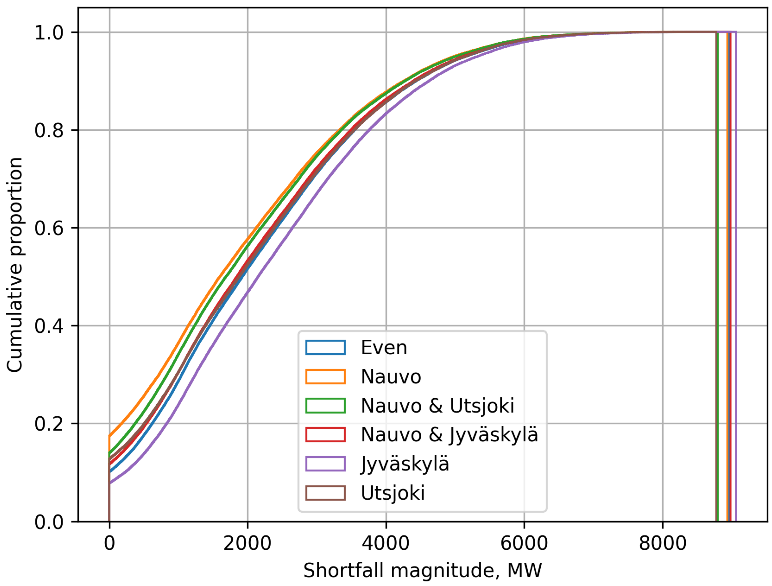

Figure 22: A cumulative distribution describing the shortfalls with 0 valued shortfalls.

Figure 22 shows that for Nauvo, the proportion of no shortfalls is around 18%, whereas for portfolios containing Jyväskylä, the value is approximately half of the one of Nauvo. The Figure 22 also shows that with the zero-shortfalls, the average magnitude, i.e., the magnitude which is likely to occur with probability of 50%, of a shortfall ranges between 1 800 and 2100 MW, being the smallest for Nauvo and largest for Jyväskylä.

Relaxing the restriction of zero combustion power, the magnitude and frequency of shortfalls with comparison to the allowed threshold level of combustion capacity are described in Figures 23 and 24. The Figures show, the average probability and the average magnitude of a shortfall depending on the share of combustion available in each portfolio.

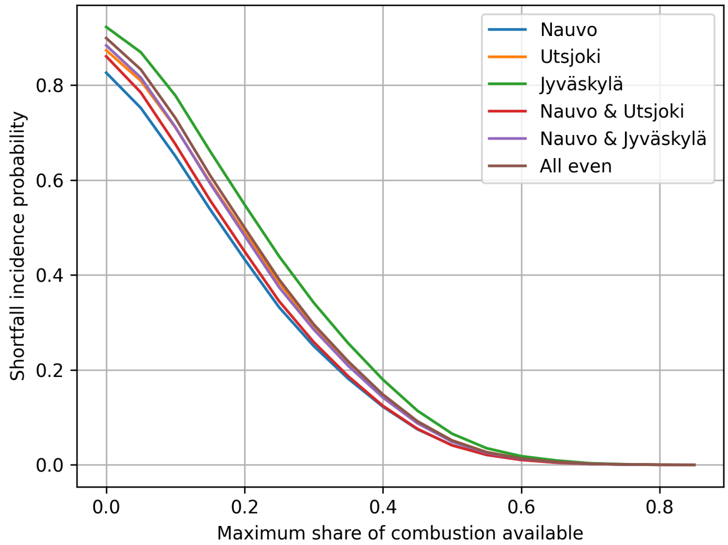

Figure 23: The probability of shortfalls with respect to the maximum allowed share of combustible power.

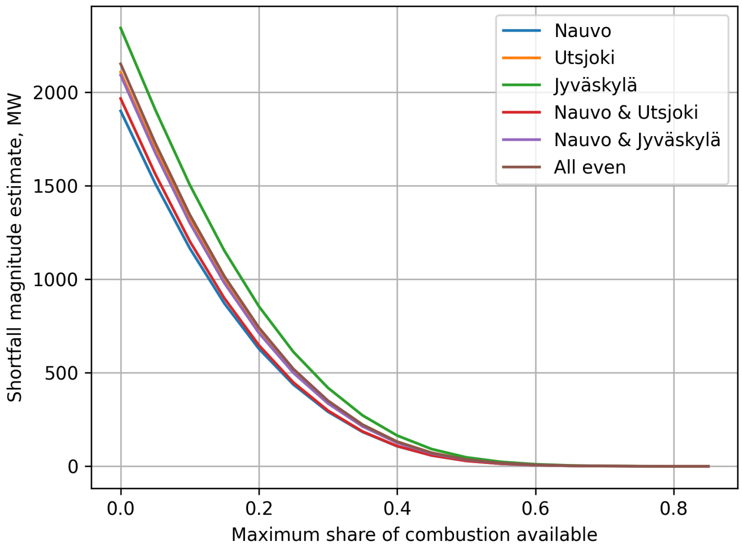

Figure 24: The magnitude of shortfalls with respect to the maximum allowed share of combustible power.

The results of the relaxed consideration are presented in Figures 23 and 24. Results are similar to those seen earlier. The Nauvo as well as Nauvo and Utsjoki exhibit the most favourable results whereas Jyväskylä results in highest probability and magnitude of a shortfall. This consideration shows that the dispatchable combustion power has a great effect on the shortfalls, which suggests that a dispatchable energy reserve is beneficial.

4.5.2 Capacity factor shortfall

Investigating the shortfalls in terms of capacity factors, the consideration is restricted to the wind power capacity factors. The simplification due to the solar PV only produces an negligible amount of electricity with the estimated capacities compared to ones with the wind power. Figure 25 illustrates how the average probability of a shortfall depends on the wind power capacity factor.

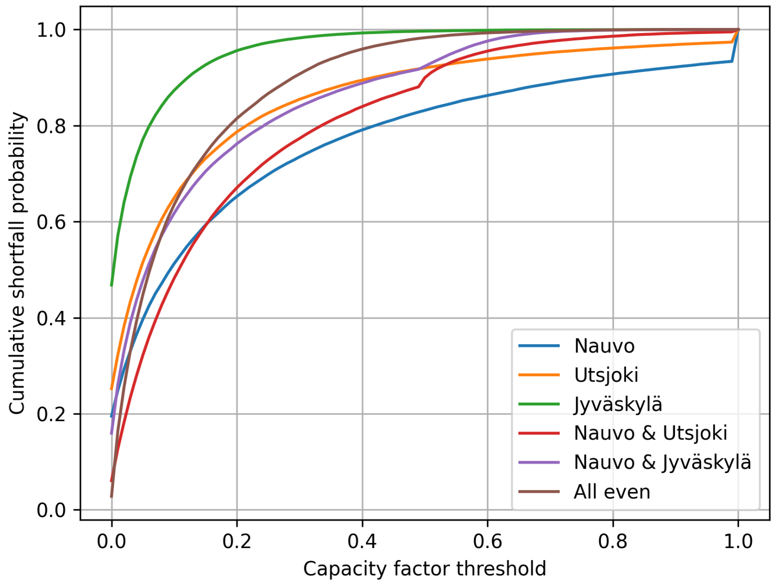

Figure 25: Probability of a shortfall incident below the capacity factor threshold.

As seen in Figure 25, Jyväskylä reaches the probability 1 with very low capacity factor thresholds which indicates that vast majority of the capacity factors are small. However, the difference between Nauvo and the Nauvo and Utsjoki portfolios is more interesting. In the early stages, the probability of an shortfall is higher in the case of Nauvo, but the situation turns around at around threshold of 0.17.

This, together with the Nauvo and Jyväskylä portfolio, indicates that portfolios with spatial distribution of production decrease the probability of a total loss of production. This can also be noted from the all even portfolio which has the smallest probability of an absolute capacity factor shortfall.

The benefit of lower risk of shortfall comes with a cost. As the portfolio of a 100% Nauvo seems to have superior capabilities, the cost of spatial distribution is the decrease in production. The spatially distributed portfolios also result in less high values in capacity factors. Therefore the conclusion is that a more reliable but less producing portfolio is can be achieved by combining low-correlated high production areas. However, if the goal is to maximise the total production, a opportunistic choice of the highest production alternative Nauvo seems to be the optimal.

Figure 25 also shows other interesting features. At the threshold 0.5 a clear bend in the case of distributed portfolio is observed. This most likely implies that there is a relatively large amount of timesteps, where the other location results in full capacity factor and the other only in a very small capacity factor. Moreover, especially the portfolio containing only Nauvo shows a steep increase at the threshold 1.0, which implies that there is a relatively large amount of timesteps where the capacity factor equals to 1. For the distributed portfolios such effect is not as probable, mainly due to spatial distribution.

5 Discussion

The goal of this work was to investigate the shortfall phenomenon and find means for visualizing and measuring the phenomenon. The utmost goal could be described as sense-making the phenomenon related topics, as all in all, the subject is board and diverse. The result of this work contributes to the goal of the research in meaningful way and has pointed out several topics for future research.

5.1 Reflection on literature

One part of this work was the literature review presented in Chapter 2. The literature review revealed that there are a myriad different models for modelling the future climate. As the future climate data is essential for research of shortfalls, the standardization and coordination of the models is important. One example of these institutions is the WCRP coordinating the research projects with projects like the CMIP. The most important factor in evaluation of the result and in intercomparison of models could be argued to be the SSP and RCP scenarios, which standardize the scenarios. Moreover, the historical data sets, maintained and developed by projects like CMIP6, are important.

Moreover, the research related to shortfalls is not very comprehensive. All in all, in the climate and climate change related research, the projects seem to concentrate to highly specific topics, this makes the understanding of complex topic, which is related to many other subjects on the field difficult. A concrete example of the difficulty is simply the generation of production or demand data. The data is needed in almost all research topics, but all projects tend to generate their for specific purposes. This generates a lack of commonly used methods and again complicates the understanding, as there is need to be able to compare the different demand models before gaining the ability to generate the data. Despite these differences, having gained some understanding on the topic, one realizes that the methods are on general level similar, only the nuances, often related to the research at hand vary. This allows finding justification for selection of methods by comparing to other studies. An example of this is e.g., the selection of the power conversion functions.

Related to this project, the methods used in this project are similar to ones used in studies published in refereed journals, which suggests that the results of this work represent the common understanding within the field, which again justifies the results.

The topic of climate change is complex, but important which has motivated developing huge, sophisticated models, which are able to do well-reasoned predictions of the future circumstances, aiding the decision making. An example of these is the automatic model by Mattson et al. [22]. Yet, the sophisticated models tend to be very complex and difficult to use for exploratory analysis. This work also contributes to this issue by suggesting a simple framework for shortfall data generation and simple, yet reasonable metrics for measuring the severity of the shortfalls.

Essentially, the estimation of shortfall data is in a sense prediction of future based on predicted data. This kind of predictions usually have very high variance, as the results are sensitive to deviations in initial conditions and parameters. This should always be noted when considering the predictions on simulated data. Moreover, as one can easily conceive, the used methods for data generation have great effect on the results. Thus, selection of methods and parametrizations, e.g., the selection of conversion functions and their parametrization has great effect. The high influence of parametrization should be complemented by conducting verification and validation studies on proposed models. This is a key element in providing justified results in the field of Operations Research,

Despite the posed critique on the prediction based on simulated data, these kind of research projects have significant meaning. Even sensitive models tend to be better in sense-making, which is the main goal of this project, and in general very important in the concerning the climate change. As the topics are complex, it is important, that the policy and decision makers can be provided information depicting the phenomena at hand on understandable level.

5.2 Assessment of the results

The quantitative results of this work, not only contribute to the goal of increasing understanding but also highlight some important phenomena.

First, the results show that, if all available capacity is utilized, there are no shortfalls events. Yet, in the light of the rough approximations and heuristic approaches, the shortfall events can be made visible. However, this work only considered cases where the production of combustion technologies is somehow partially limited. This approximation illustrates an idea on how the shortfall phenomenon actually behaves and occurs but any more detailed conclusions should not be drawn due to the limitations of the modeling.

Even though the results should not be analyzed without qualifications there are hints of phenomena that make sense also from a heuristic point of view. One of the main questions of this study, the existence and frequency of possible shortfalls, need to be addressed with caution given the results suggested shown in the data.

To produce more accurate results, a study with more sophisticated and accurate model would be needed. Despite, a more detailed study being able to yield clearer results, the findings of this study suffice for some conclusions. As a result, spatially distributing capacity indeed does make a difference in the overall situation. The results suggest that the spatial distribution decreases the volatility of the production. This suggests that with appropriate portfolio selection the possible shortfalls can on average be smaller in magnitude but on the other hand the high production season also diminish in magnitude. This implies that the hedging of the production comes with a cost. For example, the data shows how distributing capacity decreases peak production more than it decreases the low production. However, the result might vastly be caused by the limited and approximated amount of possible production locations.

Considering the results on VRE production, there are locations can easily be justified to be non-optimal producing electricity. This is mainly due to the Finnish energy production system being estimated to have almost no solar PV capacity. If the system had solar PV capacity high enough to have some meaningful impact, the result would not be obvious. Furthermore, it does seem to make sense to optimize the locations for VRE plants both from a spatial correlation point of view as well as from the total capacity utilization point of view. Considering a planning of a production system, it would suffice to invest in to system which would have both adequate shortfall resistency and production, in real-life scenario, there would be no additional value to distribute the production spatially, as in this work, is done to highlight the spatial effect.

Another finding is how the theoretical need for combustion technologies vastly decreases in the EUCO scenario. This suggests that the decrease of use of fossil fuel is indeed feasible in order to mitigate the climate change.

However, reducing capacity of fossil fuel raises two question. First question is that what is the difference of an economic impact of overly installed backup capacity and the possibility to buy electricity for a price that would only temporarily increase in case of a severe shortfall. This question would need a more economic approach to shortfalls and electricity markets. The second question is the security of supply. In case of disruptions in energy markets, having enough dispatchable capacity is a matter of security. Thus, the climate view is not the only relevant issue related to the investments, as the ability to produce enough energy has imminent value.

5.3 Future research

The models are limited. The spatial approximations are a significant limiting factor when it comes to any studies on the spatial distribution. The electricity market, technology utilization methods and demand modeling could be done in more detail.

In this work, all the combustion technologies were assumed to be similar and hence were combined. The separation of combustion technologies would give more detailed results. Moreover, the separation of the different combustion alternatives would allow considering these alternative from the emission point of view such that, e.g., only coal power and peat would be restricted and gas would yet be feasible all the time. Additionally, for the utilization of technologies, a more detailed hydro power modeling would be required. More detailed modelling would likely changes in the results significantly, since a reservoir usage of the hydro power could be used to smooth out some of the higher magnitude production shortfalls.

The current relies on a roughly approximated spatial data. The data having a grid resolution of approximately 200 km, limits the interpretations notably. Moreover, the low resolution of the model forces some coastal location to be approximated to locate fairly deep in the inland, which inevitably affects especially the wind conditions. Furthermore, in this work, only onshore production is considered, whereas offshore production would be good to include.

The electricity markets in this work, the model is simplified. In the model, the explicit pricing of the production methods was omitted to reduce the error in parametrization and to increase generality. Additionally, the interaction with other electricity markets, i.e. importing and exporting electricity, would make the model directly more realistic. A key observation in this work is that the generation of electricity is enough to cover the demand; but in the shortfall situations, when the low-cost alternatives become largely unavailable, the price increases due to introduction of dispatchable alternative. On one hand, this effect would be alleviated if there would be a change of interacting on markets, but on the other hand, this would require even more extensive modelling and parametrization as also the market interfaces to all other grids would need to be considered. In the future research a key topic is to consider the effect of electricity markets in the shortfall events.

All in all, the future demand is difficult to predict, especially given the discussion on flexible demand grids and varying understanding on the future trend of demand. For further studies, some sort of case analysis on different demand scenarios would be interesting, as the demand profiles have significant effect on the results and are estimated to change in the near future.

5.4 Conclusions

The goal of this work was to increase understanding related to shortfall as phenomenon and introduce methods to investigate the effects. In this report, methods for generating the shortfall data from outputs of a future climate scenario are presented. Moreover, this work presents some simple considerations which can be applied to investigate the effects of shortfalls. Additionally, this report has conducted a thorough literature review on state-of-the-art methods, which increase understanding on the topic.

As a result, higher penetration of VRE in current power grids is possible in future climate. The effect of variation of the VRE is notable, but with a careful and anticipatory planning, the effects can be accounted such that the disturbances are in general controllable with energy reservoirs. Furthermore, since investments to energy systems affect the profitability and production for decades, it is vital to study the optimality of production locations and location portfolios in advance. Moreover, a key result is that spatially distributing the production capacity likely results into a more predictable production.

The most important observation in this work is that the production of electricity is never independent of the electricity market. This is due to that, the electricity market infers the production of electricity via demand. As the production in a conventional electricity system, such as one considered in this work, is able to meet the demand at all times, if all the capacity is used. Thus, the production decisions are regulated by the demand. This means that the dispatchable methods are used only when the demand is either large or the production of the VRE alternatives, being the cheapest alternative, is low and there is need for supplementary power. Thus, the demand, and on the other hand, the price, inferred from the market seems to regulate the production. According to supply and demand principle, the production has effect on the market, but in this case, the demand is more powerful, when there is an underlying overproduction. The production cannot drive the demand, but the demand clearly drives the production decisions.

This is important, when considering the shortfall phenomenon, as from the modelling point of view, as the finding motivates careful and accurate consideration of the energy markets, as otherwise there will be no shortfall events. Thus, if the electricity market model and the demand profiles are not realistic, the production affecting the pricing is not a sensible either. Hence, the electricity market is in the heart of future production system modelling, at least when the shortfalls are considered.

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A Self Assessment

A.1 Project plan with respect to the project

A.1.1 Scope

The initially set scope was thought to be feasible. In the end, the project, however, ended up being slightly over the scope in terms of workload. Main reasons for this could be that the amount of details along the path to the goal was slightly underestimated. However, one could also argue that the project was done in more detail than initially planned. For example detailed research on the climate model was not expected to be as thorough as it finally ended being. Yet, in order to get meaningful results, all the intermediate step needed to be done well. In hindsight, if there would have been less work to do with the data, the issues related to the details could have be noted much earlier.

A.1.2 Risks

One of the main risks, i.e, the loss of a team member, realized twice during the project. The loss of a team member probably ended up being the most significant realized risk. However, also a risk related to the size of the scope and workload realized but was in some sense a result of the loss of two team members.

Without the loss of two team members, the workload could have been better divided. There were clear areas, which could have been taken care of by just a single person. However, the aim to proceed in an agile way was likely way easier with the remaining team of two since communication and decisions related to the project were easily done. Moreover, there was less need to stay updated about recent developments in the project since the two team members were constantly aware of the overall status and recent developments in the project.

The support of FMI, especially Tommi Ehkolm, steered the project well to a meaningful direction. This essentially prevented the workload to exceed the intended too much. Moreover, the support helped to validate and choose each iteration and step better.

A.1.3 Schedule

The schedule in general was well met. There was an internal deadline set to the beginning of May, which played an essential role in hurrying up with the project at the last minute. The internal plan was not accurately met but it gave a good basis for completing the project on time.

The last iteration of the project was probably the most challenging when it comes to the schedule. The initially planned final iteration was abandoned due to a better new idea for this step. However, this resulted in some more analysis and research, which exceeded the planned workload. This was the main cause for the final rush and a slight delay to the initial deadline.

A.1.4 Project execution

The project execution was easy. The team, as well as the client, were highly motivated and committed in completing the project. This made the overall execution smooth and motivating.

In the end, the general way-of-working was a weekly team meeting with the project team and approximately a monthly meet with the client. The client meetings were highly driven by a significant reason. This is why the meetings were planned in accordance with demand. Moreover, the results were discussed and evaluated with a team of clients. This meeting provided good understanding on the topic domain and reasons for the results obtained.

A.1.5 Amount of work

The amount of work heavily concentrated on two parts, handling and importing the raw data and building the analysis pipeline, as well as the writing of the final report. Other than this, the project was relatively low on workload and provided a good balance of investing time on analysis and receiving results.

The raw data, especially the climate data, was complex to extract and put in a required form. However, after this was done well, the analysis and handling of data and results was relatively easy and quick.

The writing of the final report was probably the most significant part of the work. Especially the description of the data and the literature review were heavy on the required hours to complete. However, the chapters of these topics could have been done in less detail, but not all of the important information could have been stated.

A.2 Successfulness of the project

The project, in general, was successful in what it was initially planned to offer.

One of the main goals of this project was to have a sense-making report that would describe the complex and generally in much detail explained phenomena well. The project teams considers this goal was well achieved.

Another major achievement this project was seeking answers to was the nature and impact of shortfalls. Despite the lack of details required to answer this in full detail, relevant results were also found for this question.

A.3 Not successful in the project

The level of approximations was eventually higher than initially expected. Given this, the results are not as trustworthy as the were initially hoped to be. However, one of the results was that with the scenario used, no shortfalls should ever happen. This resulted in better understanding of the phenomena related to shortfalls and basically meant that much further analysis should be carried out to see what are the real fears of shortfalls in the case of Finnish future energy and climate scenarios.

A.4 What could have been done better

Studying the literature in more details in the beginning could have steered us towards the final analysis faster. However, one may also argue that the current way of working increased the motivation for own analysis with the support of the client. Related to the same topic, in the project, a better grip on the workload and schedule could have been held. As the project was set to be 7 + 5 credits, the project team should have adjusted the scope accordingly.

A.4.1 Team

The workload could have been better divided during the project. Now a significant work load was left for the last weeks, which made the end of the project more intense as wished.

From the organizational point of view, the project did not really teach much new. The loss of a half team resulted in an extremely agile team which made the organization of the team nearly irrelevant. Moreover, the team members knew each others well before the project, which further decreased the possibility to learn more about team working.

A.4.2 Teaching staff

The professional competences of the client made the need for teaching staff nearly irrelevant in terms of support. Moreover, half of the team consisted of half of the teaching staff, which made the line between the teaching staff and the team blurred.

A.4.3 Client organization

The client was very competent and supportive during the whole project. We had good balance between the support received and the amount of individual work.