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Reliability of electricity in Finland during the energy transition

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Abstract

In this work, the reliability of electricity in Finland is investigated when wind power production increases. Wind power is an intermittent source and depends on the weather and thus affects production in varying ways. The topic is current because energy transition is accurate.

Electricity reliability refers to the power system's ability to deliver electricity consistently with minimal disruptions and interruptions. It is important to cover electricity consumption at every stage and it should be covered in the future as well.

The work includes a literature review that covers the research. The purpose is to study the reliability of electricity from different perspectives and to answer the research questions with the help of modelling. The work focuses especially on residual demand and its effects. In addition, the work considers whether demand can be met with other sources.

Wind power production and electricity consumption will increase in the future. In order to cover it, a lot of other capacity will be needed in the future in addition to wind power. During periods of high consumption, wind power production will be low in the future. The transition to renewable energy increases uncertainty and fluctuations in the electricity system during the energy transition.

Keywords Energy transition, reliability of electricity, residual demand

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Tiivistelmä

Tässä työssä tutkitaan sähkön riittävyyttä Suomessa, kun tuulivoiman tuotanto kasvaa. Tuulivoima riippuu säästä ja vaikuttaa siten vaihtelevasti tuotantoon. Aihe on ajankohtainen, koska meneillään on energiamurros.

Sähkön riittävyydellä tarkoitetaan sähköjärjestelmän kykyä toimittaa sähköä johdonmukaisesti minimaalisilla häiriöillä ja katkoksilla. On tärkeää kattaa kulutus jokaisena hetkenä ja siihen on varauduttava myös tulevaisuudessa.

Työ sisältää kirjallisuuskatsauksen, joka taustoittaa tutkimusta. Tarkoituksena on tutkia sähkön riittävyyttä eri näkökulmista ja vastata tutkimuskysymyksiin mallinnuksen avulla. Työssä keskitytään erityisesti residuaalikysyntään ja sen vaikutuksiin. Lisäksi työssä pohditaan, voiko muilla lähteillä kattaa kysyntää.

Tuulivoimatuotanto ja sähkön kulutus kasvavat tulevaisuudessa. Jotta sähkö riittää, tarvitaan tulevaisuudessa paljon muuta kapasiteettia tuulivoiman lisäksi. Korkean kulutuksen aikana tuulivoimatuotanto on alhaista tulevaisuudessa. Siirtyminen uusiutuvaan energiaan lisää epävarmuutta ja heiluntaa sähköjärjestelmässä energiamurroksen aikana.

Avainsanat Energiamurros, sähkön riittävyys, residuaalikysyntä

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Preface

I would like to thank my supervisor Ilkka Keppo for giving me the opportunity to work on this thesis topic and for helping me actively throw the process. I would like to also thank my advisor Iivo Vehviläinen for his thoughts and help with the modelling.

I am proud of myself that I have actively worked on this thesis and that I have been motivated throw the whole process. It has been nice to work on this topic.

Now, I am ready for new challenges and opportunities that the future brings with me. Aalto University has thought me important skills and provided people that stays for the whole life. Thank you to everyone who has been part of my journey.

Espoo, 31.07.2023
Henrietta Hirvonen

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1 Introduction

This chapter outlines the entire thesis. In the beginning brief background is presented. Next, the research questions and motivation are discussed. Lastly, the research scope is given, and the structure of the study is presented.

1.1 Background

Decarbonization of the energy system is one important challenge. The energy sector produces two-third of global carbon dioxide. The main challenges are the growing demand of electricity, the reduction of greenhouse gas emissions, and meeting the Paris Agreement. (Kabeyi, 2022) This means that energy transition needs to focus on switching from fossil fuels to renewable sources. Renewable energy sources in the share of electricity produced are expected to increase significantly by 2030.

Wind power is one of the fast-growing and cleanest electricity generation technologies. The increasing amount of wind power affects the reliability of the electricity supply in the energy system. The intermittent renewable sources cause uncertainty in electricity supply that impacts grid stability and reliability. It is important to have backup generation and energy storage systems that can provide power during periods of low wind generation. Batteries can help store electricity and release it when needed.

Promoting renewable resources has established environmental policies. The increasing number of renewable energy sources has introduced challenges for the markets. Electricity producers must take into consideration the fluctuation in load and infeed of renewable energy. The increasing amount is challenging for grid operators from the perspective of grid stability and the security of supply. Demand and supply need to be in balance. (Do et al, 2021)

Nord Pool is a wholesale power market in Finland that connects with nearby countries. (Jääskeläinen et al, 2018) It operates on a day-ahead basis, where electricity producers and consumers submit their bids and offers. Based on these submissions, Nord Pool calculates the price for each hour of the next day. This pricing mechanism ensures a balance between the amount of electricity available, and the amount needed, aiming to produce electricity at the lowest possible price for each hour. (Huang and Liu, 2006) Affordable wind power is shaping the electricity market.

Electricity plays an important role in daily life and operations. The demand will grow and therefore structural changes are needed to change to be more sustainable. In Finland, the electricity sector relies on renewable energy, nuclear power, and import from neighboring countries. Finland has the second-highest share of renewable energy in the EU. (Energiateollisuus, 2020)

The security of electricity supply can be divided into two elements: the adequacy of electricity and the operational security of electricity networks. Electricity power sufficiency means that the domestic production of electricity or imported electricity received from neighboring countries is sufficient to cover the current electricity consumption need. Security of supply in electricity networks means that there are no interruptions in the electricity network that prevent uninterrupted electricity transmission to the customer.

1.2 Structure of the thesis and motivation

This thesis investigates the reliability of electricity in Finland during high demand. The study consists of a literature review and modelling part.

The main research questions are:

- How will the increasing amount of wind power influence the reliability of electricity supply in the future?

- Are there any problems with electricity reliability?

The goal is to study the meaning of total demand and residual demand, the effect of wind power on electricity supply, and if other electricity sources are needed to cover demand. Residual demand curves give valuable information. It is connected with wind power production and other sources that are needed to meet the demand. The motivation behind analyzing residual demand is connected to ensuring that demand meets the supply. Understanding residual demand plays a key role in ensuring reliable electricity supply while diverse energy sources are incorporated, and fluctuation is happening. Currently, still, some of the residual demand is covered with fossil fuels.

This thesis answers these research questions and investigates the meaning of wind power production that is increasing. The connection is interesting and plays a key role in the future. Forecasting, if the electricity supply can meet the demand in the future, is uncertain. In this thesis, the second research question is analyzed step by step with different electricity sources. The scope is in the Finnish electricity system, and it includes an analysis of the present time and the future.

After the set of questions presented in this chapter, the literature review is presented. Increased renewable generation is affecting the electricity market and is important to cover. The literature review will also discuss wind power as an intermittent source and its effect on electricity demand and the uncertainty of production. Energy storage helps during high demand and is related to research questions. Also, investments boost the energy transition and therefore affect in helping with residual demand. Trade play an important role in electricity reliability in the future and that is why this is covered in the literature review. After covering the topics in the literature review, the research material and methods are presented. Then the thesis provides the models and own analysis of the results. Finally, the conclusion is provided.

2 Literature review

In this section literature review is presented. The purpose of the literature review is to cover the topic from different perspectives. The reliability of electricity is investigated in this thesis from energy transition, wind power production, reliability, energy storage, investment, and trade perspectives.

2.1 Energy transition and role of electricity market

There is an ongoing energy transition where renewable energy sources replace fossil fuels. The share of intermittent sources such as wind power has increased rapidly and is affecting the reliability of electricity. It complicates the function of the grid because they are weather dependent which creates a need for flexibility.

In the current decade, the electricity market is undergoing significant transformations due to operating conditions and ongoing energy transition shifts. These changes necessitate the development and adaptation of the electricity market to meet the evolving demands and challenges. A well-functioning electricity market provides a security supply that is considered sufficient by the market and ensures a cost-efficient transition to a low-carbon power system. The market model needs fixing because the current can lead to the risk of supply. (Fingrid, 2022) Electricity sufficiency is affected by electricity consumption and consumption flexibility, available electricity production capacity, and electricity that can be transferred via electricity transmission connections from other market areas.

It is crucial to ensure that the electricity market model aligns with the goals of achieving a carbon-neutral energy system, maintaining system reliability, and optimizing cost efficiency. The current state of electricity markets is unsustainable, and a new market model is necessary due to the rapidly changing structure of electricity generation. The existing market mechanism and power adequacy are at risk. Various factors have led to the need for a new market model, including technological advancements, environmental objectives, consumer demands, and pricing signals.

2.2 Wind power production

Wind power is a fast-growing renewable energy source. Wind power capacity increased significantly by 75 % in Finland in 2022. In total 2 430 MW of wind power were built. These investments were together worth 2.9 billion euros. Wind power increases Finland’s self-sufficiency rapidly. There is no other electricity production that can be built as quickly and cost-effectively as wind power. As wind power additional construction is increasing it will however slow down to 1000 MW annual level. (Mikkonen, 2023) Wind power is categorized into onshore and offshore wind production. The offshore wind takes place outside land and is typically producing more electricity.

Wind power is intermittent and increases the uncertainty of net load because the power can’t be predicted at all time horizons. Wind power is dependent on weather for capacity availability. The output depends on wind speed and therefore the maximum power will vary over time. There is a possibility of forecast errors which causes problems with adequacy. (Cochran et al, 2013)

Wind power has low operating costs because there are no associated fuel costs. (Wind Exchange, 2015) It is operated at its maximum available capacity for most of the time. The uncertainty and variability of wind can lead to an increased frequency of price swings.

There are several barriers that can limit the deployment of wind power. Mostly, the reasons are related to nature values, opposition from local citizens and politicians, and the competitive situation between project developers. (Valtioneuvosto, 2022) The development of wind farms can sometimes face public opposition, particularly if the projects are located in areas with high visual impact or potential impacts on wildlife. Wind farms require a significant amount of land, which can be a barrier in densely populated areas or in areas with competing land uses, such as agriculture or conservation. Wind power requires a significant investment in grid infrastructure to ensure that it can be reliably integrated into the electricity system. This may involve upgrading transmission lines, building new substations, and improving grid management systems. Wind energy’s potential will depend on policy developments in the major energy priorities. Even when the sign is positive towards wind energy there can be a lack of enabling policy frameworks and regulations. (Corbetta et al, 2015) Long-term visibility and a stable framework remain crucial for the development of wind energy. The projects rely on land availability, grid connections, and wind resource. Projects can’t always be developed in areas where grids are. (Pettersen et al, 2022)

Wind power creates highly unpredictable deviations in supply. The challenges in electricity storage cause the necessity for supply and demand to match the equilibrium. When there is a lack of wind, other supply should be increased. (Gerasimowa, 2017)

2.2.1 Balance of wind power and electricity demand

Balancing wind power and electricity demand is a critical challenge in the integration of renewable energy sources into the power grid. The weather-dependent wind power can create imbalances between electricity supply and demand. The balancing process requires collaboration between grid operators, consumers, and energy providers. The balance will continue to improve as renewable energy technologies advance and become more integrated into the grid.

The increase in the construction of wind power in Finland began in 2012–2013, and since then the amount of wind power has increased at an increasing rate. The importance of wind power in Finnish electricity production will increase significantly in the near future. (Koskela, 2022) Increasing wind power production in the Nordic countries will pose future challenges to the security of supply. This can be solved either by storing energy, shifting consumption or by increasing the production capacity in the system. (Känkänen, 2016)

Due to its fluctuating production, growing wind power production requires parallel control power in order to maintain the power balance of the electricity grid. A larger amount of wind power would require increasing the energy efficiency of consumption, and flexibility between energy production and consumption. This flexibility could be achieved with energy storage. Another way to increase the control power is with smart electrical networks. (Passila, 2020)

2.3 Reliability of electricity

Reliability in the context of electricity supply refers to the ability of a power system to deliver electricity with minimal disruptions and interruptions consistently. Demand response programs and efficient load-balancing mechanisms help manage fluctuations in electricity consumption. It ensures a stable supply during peak demand periods. (U.S Department of Energy, 2023)

The problem of ensuring a reliable electricity supply consists of two main aspects. On one hand, it involves the short-term capability of the electrical system to handle unexpected disruptions and maintain stability. On the other hand, it encompasses capacity adequacy, which ensures that there is always enough aggregated electrical supply to meet the demands and requirements of customers. It's crucial to maintain strong connections between market design, reliability, system planning, and operational strategies. (Fionin and Pignon, 2008)

2.3.1 Flexibility

Market flexibility can be improved by offering consumers the opportunity to actively participate in the market by adjusting their consumption according to real-time prices. Ensuring that the market provides the right signals for investment in production and the efficient use of available resources improves flexibility.

Demand flexibility makes the operation of the electricity market more efficient and can influence the market price of electricity. Demand flexibility is clearly the most effective, cheapest, and fastest way to influence the market price of electricity and the electricity procurement costs for companies. (ELFI, 2015)

Flexibility is a challenge. With uncertain wind power, the resources in systems will have to be more flexible with output. The goal of system and market operators should be to utilize the flexibility of the system to meet reliability requirements as cost-effectively as possible. Lack of flexibility can lead to production and load imbalance, overloading of transmission elements, and other potential reliability problems. (Ela et al, 2014)

The main operating condition of the electricity system is the constant balance of production and consumption. Typically, production has been adjusted according to fluctuations in consumption. As the production structure changes, consumption control is also needed to achieve balance. In this case, to maintain the balance, demand elasticity is even more necessary. (Harsia et al, 2022)

Changes are needed in the entire electricity system that supports momentary fluctuations in production and consumption, as well as their daily or seasonal fluctuations. In practice, there are two ways to solve the problem, all of which are probably needed. Firstly, demand elasticity solutions are needed, which can be used to change consumption to match the production at that moment. In the case of an individual consumer, this practically means directing consumption from a period of high consumption and price to a more affordable moment. Demand flexibility makes it possible at best to reduce the total consumption of electricity, optimize the use of the electricity grid, and contribute to the development of various services that improve living comfort. Secondly, it is important to develop energy storage solutions so that the difference between production and demand peaks can be smoothed out. Storage is most often associated with the development of battery technology, but other cost-effective storage methods are also needed. In addition to batteries, storage can be done by storing energy as heat or through chemical reactions as gas, which can then be used at the appropriate point as desired. (Bremer et al, 2017)

2.3.2 Energy storage

The reliable operation of the grid has become even more challenging as variable renewable energy production grows rapidly. Flexible resources are needed in the power sector. Energy storage is capable to shift demand and supply across time. Energy storage provides several benefits. By making even production over time, energy storage reduces production costs and flattens the price curve, which improves production efficiency and lowers prices for consumers. Storing electricity when the availability of renewable energy sources is high and releasing it when storage is low facilitates the integration of renewable energy sources in the electricity market. The same applies when the demand shifts from an abundance of renewable energy sources to a scarcity. Also, because energy storage and demand response promote the security of supply, they reduce the need to invest in firm capacity. (Fabra, 2022)

The familiar lithium-ion batteries from mobile phones and electric cars are in our everyday use, but they are not suitable for long-term electricity storage. On the other hand, lithium-ion batteries can support the electric grid in short-term and rapid changes that shake the balance of consumption and production. Lithium-ion batteries are thus an excellent tool to increase flexibility in the electricity system and enable more renewable electricity production. (Siilin, 2022)

Figure 1 presents the effect of energy storage in peak demand.

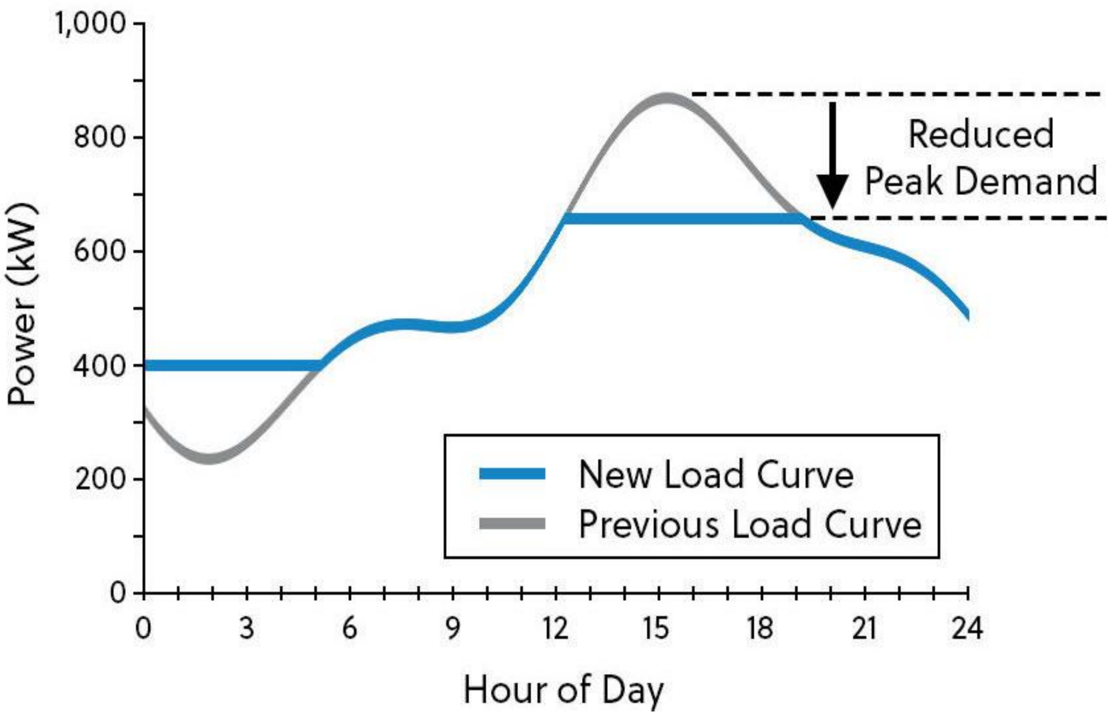

Figure 1. Peak demand reduction with energy storage (Omnes Energy, 2016)

The system can charge electricity during low usage hours and then discharge it during peak load times. This supports power quality and reliability. Batteries are used therefore for grid stability and balancing services.

2.4 Investments

In an ideal situation, the electricity market generates investments in two ways. First of all, the country is attractive for industrial investments when the electricity system is reliable, meets customers' needs, and produces clean electricity. In addition, the price level should be predictable and competitive compared to key competitor countries. The demand affects the market in a negative way where no investments are attracted. If electricity is cheap new investments are possibly made easier. (Kajaste, 2022)

The European Wind Energy Association estimates that in the longer term, wind power is still an attractive investment target because the world needs a clean and reliable form of energy production. According to the forecast, investments in the wind power industry would rise to 239 billion euros. (Tuulivoimayhdistys, 2023)

Dozens of new investment projects are being prepared in Finland. The projects are mainly based on the production of clean hydrogen and the utilization of wind power as the energy source. (Fingridin and Finlandin, 2022) From the point of view of electricity sufficiency, it is essential to assess if the price fluctuations and the high price spikes that may occur from time to time a sufficient means to cost-effectively generate the necessary investments in capacity that can be used to guarantee electricity sufficiency. (Fingrid, 2022)

Investments in the distribution network are needed. The existing networks do not have the quantitative capacity to support the technologies and sustainable energy generation. One concern for the future network is the possibility of increases in peak loads. This could be caused by changing usage profiles or by increased total electricity use. (Blokhius et al, 2011)

2.5 Future of trade

International trade of electricity opens opportunities to reduce capacity and import electricity. The Nordic countries trade electricity with each other. This helps maintain sufficient generation capacity to meet peaks in demand. (Antweiler, 2016) Importing always happens when it is cheaper than using domestic electricity generation options. Similarly, electricity is always exported when neighboring countries are ready to pay more than the domestic production price. (Energy Transition Model, 2023)

The future of the electricity trade is likely to be shaped by several factors, including technological advancements, policy changes, and shifting market dynamics. Trade and interconnection with Europe are the key elements for the Nordic countries to reach their carbon and energy targets. It helps to secure electricity adequacy in the future.

Figure 2 illustrates the Nordic electricity trade in 2050.

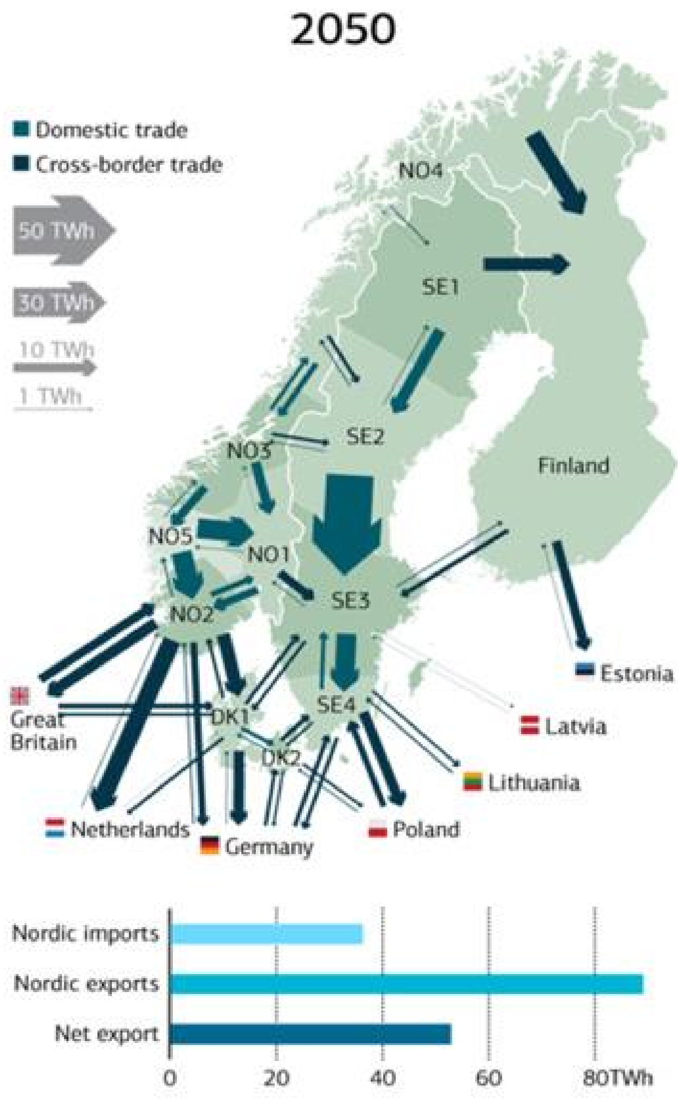

Figure 2. Trade map in 2050 (Sovacool, 2017)

Nordic export to Europe will be higher than imports. Finland will trade electricity between Sweden, Norway, and Estonia. Norway with high hydropower will play a key role in exporting electricity to Finland.

As the cost of renewable energy continues to decline and the deployment of new interconnectors increases, we are likely to see a rise in cross-border electricity trade. This will enable countries to tap into a wider range of renewable resources and balance their energy systems more effectively. The increasing digitalization and automation of the electricity sector is likely to lead to more efficient and streamlined trading systems. This could include the use of artificial intelligence and machine learning algorithms to optimize trading strategies and reduce costs. The deployment of energy storage technologies, such as batteries and pumped hydro storage, is likely to increase in the coming years. This will enable more flexible trading and greater integration of renewable energy sources into the electricity grid.

International cooperation is needed and there are benefits to expanding it. Interconnections will provide greater security of supply and reduce the generator’s market power. Also, it enables competition in generation and provides better connections for new renewable electricity.

Each country has a different degree of renewable potential. One example is where one country has plenty of renewable hydropower and plenty of thermal power plants. In this situation, cheap hydropower can be supplied in peak times. This type of complementary system will play a key role in the future. Policymakers, industry stakeholders, and consumers will need to work together to navigate these changes and ensure that the transition to a low-carbon energy system is as efficient and cost-effective as possible. (Jacottet, 2012)

3 Research material and methods

The research material approaches the reliability of electricity from different perspectives. One is the total demand and residual demand. Another one is to investigate the coverage of total demand with different energy sources in the future. In residual demand wind power production is reduced from total demand to see the correlation and effect of wind power production during high peak demand.

Different models in this thesis are answering the research questions. These models are suitable because residual demand curves give valuable information regarding the reliability of electricity. The models show how the increasing amount of wind power is affecting the security of the electricity supply. Also, fluctuation shows if the demand can be covered by other sources. The purpose of the models is to cover the reliability and security of electricity supply during the past few years and in the future.

To illustrate the models, different data is utilized. The needed data consist of electricity demand and wind power production in Finland. The data shows the results for every hour for the selected years. The data is taken from open data sources from Fingrid's website. (Fingrid, 2023) Demand and production are changing every hour. The month and timing of the day is affecting the magnitude. The data is collected, and the models are implemented in Excel.

The three years for total demand and residual demand are selected based on a windy year, less windy year and future approach. The years are 2021, 2022 and 2035. Finland has a carbon neutral target for the year 2035 and therefore it is interesting to analyze that year. The time horizon is 8760 hours. It means that every hour in a year is covered.

In modelling section assumptions are made. It is assumed that in 2035 the share of wind power would be significantly higher. In this case, hourly wind power production would have increased directly in proportion to the increase in capacity, and demand in direct proportion to the increase in total demand. Wind power is assumed to grow 4,5 times and electricity consumption is assumed to grow 1,35 times. Electricity demand is assumed to be approximately 115 TWh in 2035. It was 85 TWh in 2021. Wind power production is assumed to be approximately 14 GW in 2035 and it was 3,11 GW in 2021. These assumptions are made by Fingrid, and they are taken from their scenario. (Fingrid, 2023) In this scenario, electricity consumption is predicted to increase strongly. The significant increase in consumption assumed in the scenarios is based on a significant increase in wind power production. The growth of wind power is affected by the assumption of a decrease in its production costs. (Fingrid, 2023)

The persistence curve indicates the time during which a certain power is reached or exceeded. The most important information that can be found from the persistence curve is the peak power usage time. The peak power usage time describes the time in which the energy of the entire review period would be consumed if the energy were consumed at peak power. In Excel, demands are put in order of magnitude from largest to smallest. The biggest value is presented in the graphs at the first hour and the smallest at 8760 hours.

Fluctuation is also illustrated from the same data. It provides an easier understanding of electricity demand differences. The reader can see straight when the demand is high and when low. Analysis is also provided. It answers the question if there are any problems with reliability.

Fingrid’s electricity system vision has given inspiration and numbers for this thesis and models. It is important to understand how these values affect this thesis. The goal of Fingrid's electricity system vision is to present Finland's opportunities to compete in electricity production and consumption projects and to create a long-term view of the development needs of the main power transmission network. In addition, the goal is to identify and bring up challenges and opportunities for discussion, which the realization of the energy transition and to electricity-intensive and carbon-neutral transition to society will bring**.** (Fingrid, 2023) The analysis in this thesis differs from Fingrid’s analysis. In their analysis, the need for transfer capacity and electricity price stability is illustrated in persistence curves. The effect of residual demand is not covered.

4 Modelling

This section concentrates on modelling as the method and answers the research questions through graphs and analysis. Electricity demand is presented in persistence curves for selected years. Fluctuation is also presented from the same results, but it is illustrated in a different way. With these results, the peak demand is analyzed if it can be covered with other energy sources than wind power.

4.1 Results

Persistence curves for the years 2021, 2022, and 2035 are presented below. The y-axis shows the demand in MW and the x-axis the hours. The blue curve presents total demand and the orange residual demand.

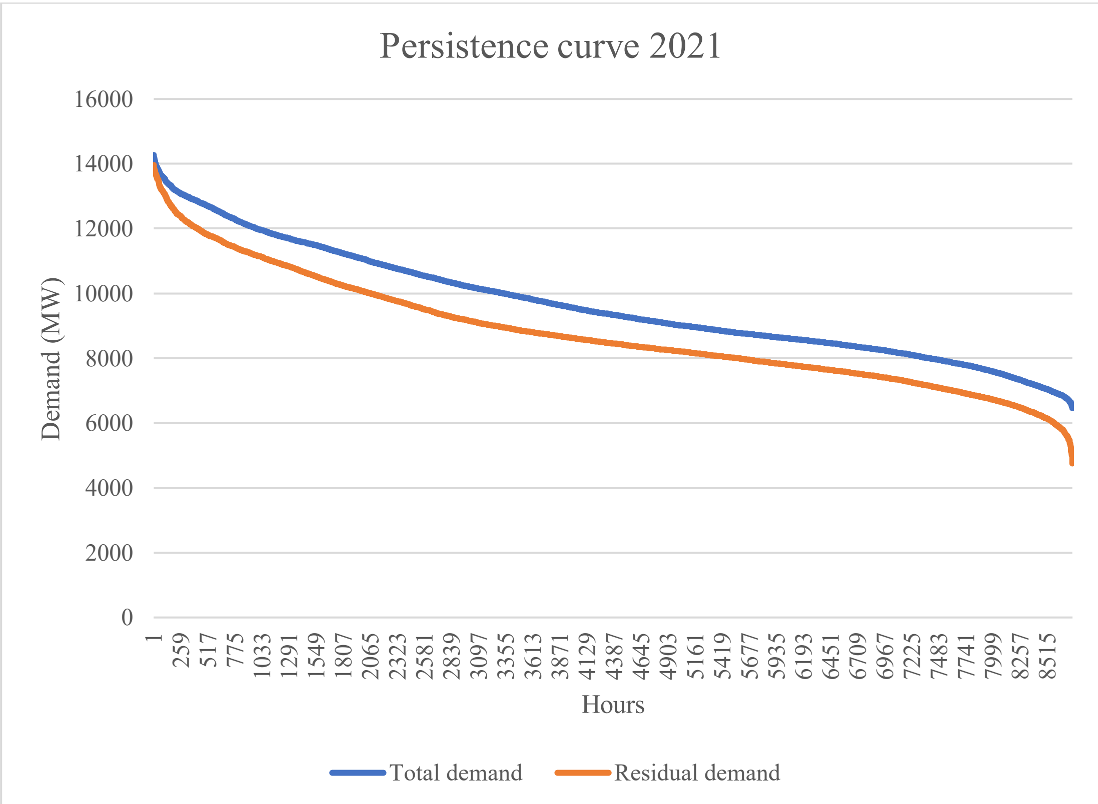

Figure 3. Persistence curve for the year 2021.

At first look, the curves seem to follow the same structure. The maximum total demand and residual demand are almost the same and therefore there is a small amount of wind power at the time of peak demand. The residual demand is lower than the total demand in the whole graph. Both curves start at approximately 14000 MW. In the beginning and in the end, the curves drop faster. The total demand curve is the steepest for a short time when the demand is highest. The residual curve is the steepest for approximately 362 hours. Wind power production is stabile for the whole year. Demands are not negative during the whole time.

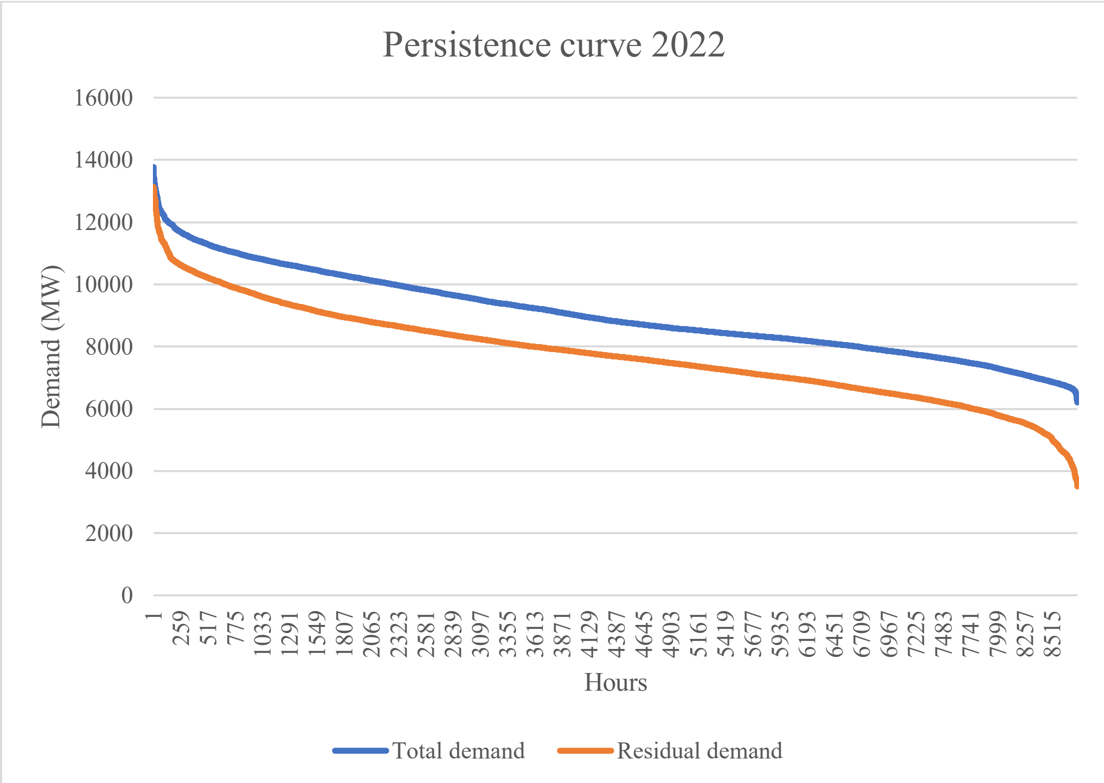

Figure 4. Persistence curve for the year 2022.

As in the year 2021, the maximum total demand and residual demand are almost the same but compared to the previous year the demands are lower. There is a small amount of wind power at the time of peak demand as well. The maximum demand in both curves is a bit lower than 14000 MW. The curves are steepest in the beginning. The residual demand is highest for a short time, approximately 280 hours. Other capacity is needed to cover the demand then. Demands are not negative during the whole time.

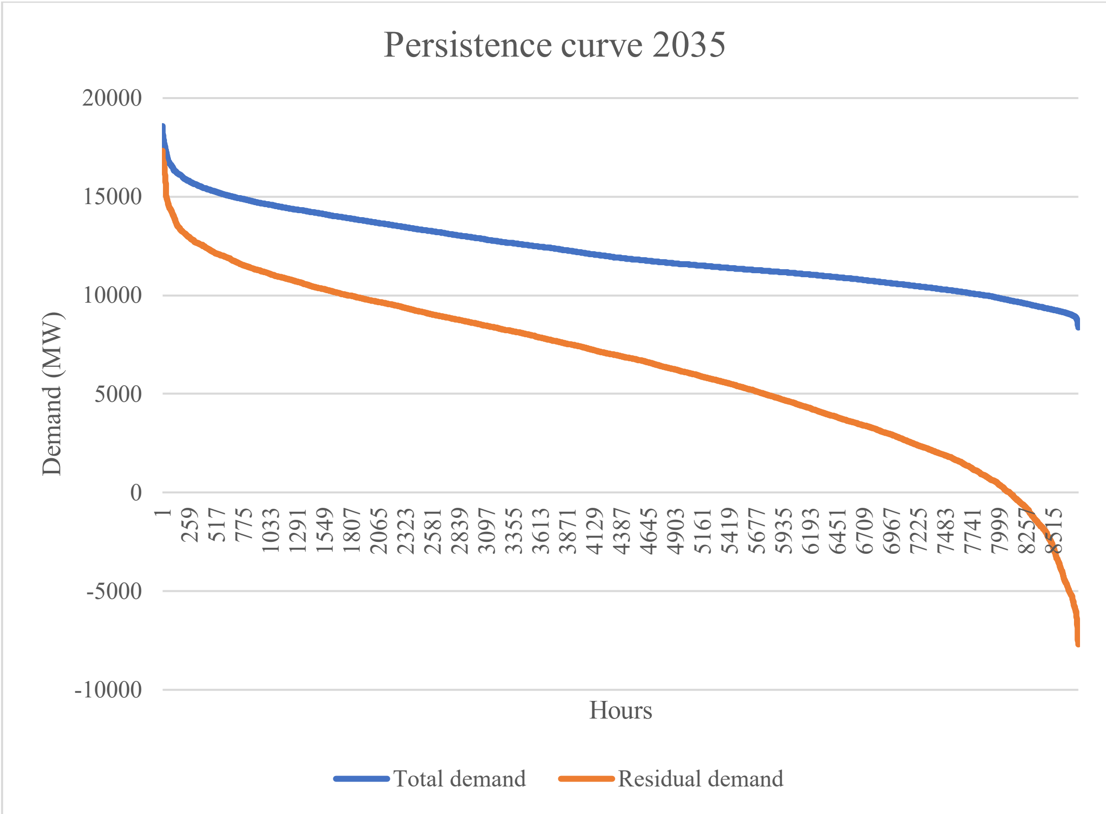

Figure 5. Persistence curve for the year 2035.

The maximum residual demand is almost the same as the total demand. The total demand is approximately 18000 MW. Wind power production is low during the high peak. The total demand curve and residual curve are steepest for a short time. The biggest residual demand occurs for approximately 200 hours and is a short time. During the highest peak hours, other capacity is needed in the 2035 scenario, even though wind power has increased dramatically.

Wind power production is growing over time. Wind power production is highest in the end, and the turbines are running at maximum capacity and the capacity is approximately 15000 MW. When the curve meets the zero point the electricity price is not more than zero and therefore the producer doesn't receive any payment for production. Residual demand is negative in the end. The difference between the curves is very dramatic and it can be seen from the graph automatically.

The total demand is usually lowest during nighttime. Wind power production is fluctuating a lot hourly. (Fingrid, 2023)

The next figure illustrates the negative residual demand in 2035.

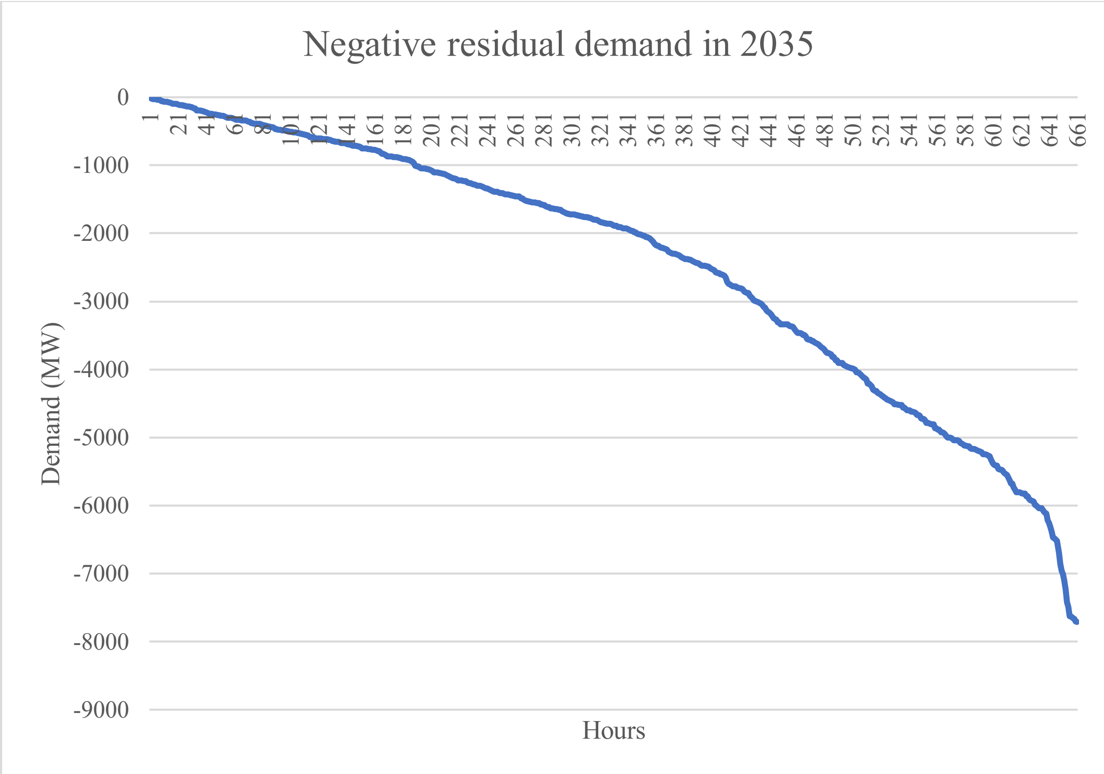

Figure 6. Negative residual demand in 2035.

During negative residual demand, there is wind power production more than other production. It is windiest then. Residual demand is negative all together 661 hours during the year 2035. The negative curve presents the time when producers need to pay for supplying electricity. During these hours it is not profitable for producers. The curve is negative only in 2035.

The next figure shows the difference between residual demand curves in 2022 and 2035.

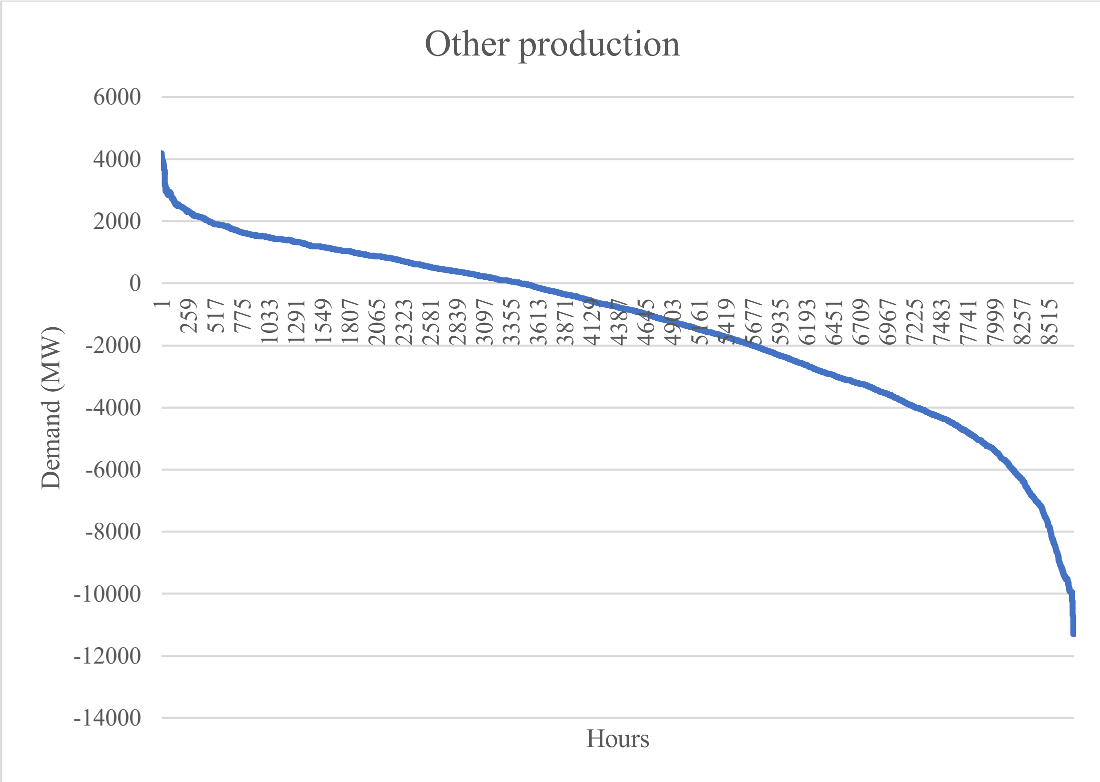

Figure 7. Difference between residual demand in 2022 and 2035.

The figure presents the amount of other production. In approximately half of the time other production is above zero point and half of the time under zero. Residual demand is higher in 2022 than in 2035.

Much more wind power has come between these two years, and then other capacity is not necessarily needed. Demand rises between these times. So, no other energy would be needed, but if there is no wind, then it is needed.

The next figures illustrate the fluctuation of demand in 2021, 2022 and 2035. Demand is presented in y-axis and hours of whole year in x-axis.

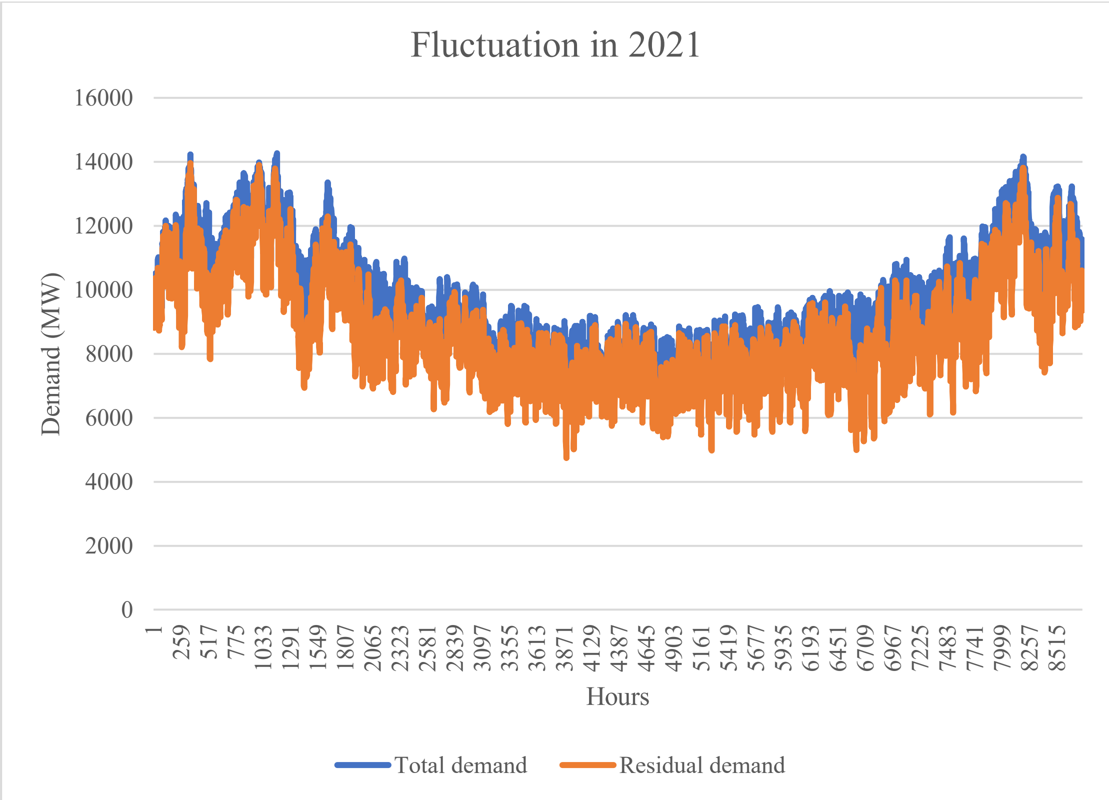

Figure 8. Fluctuation in 2021.

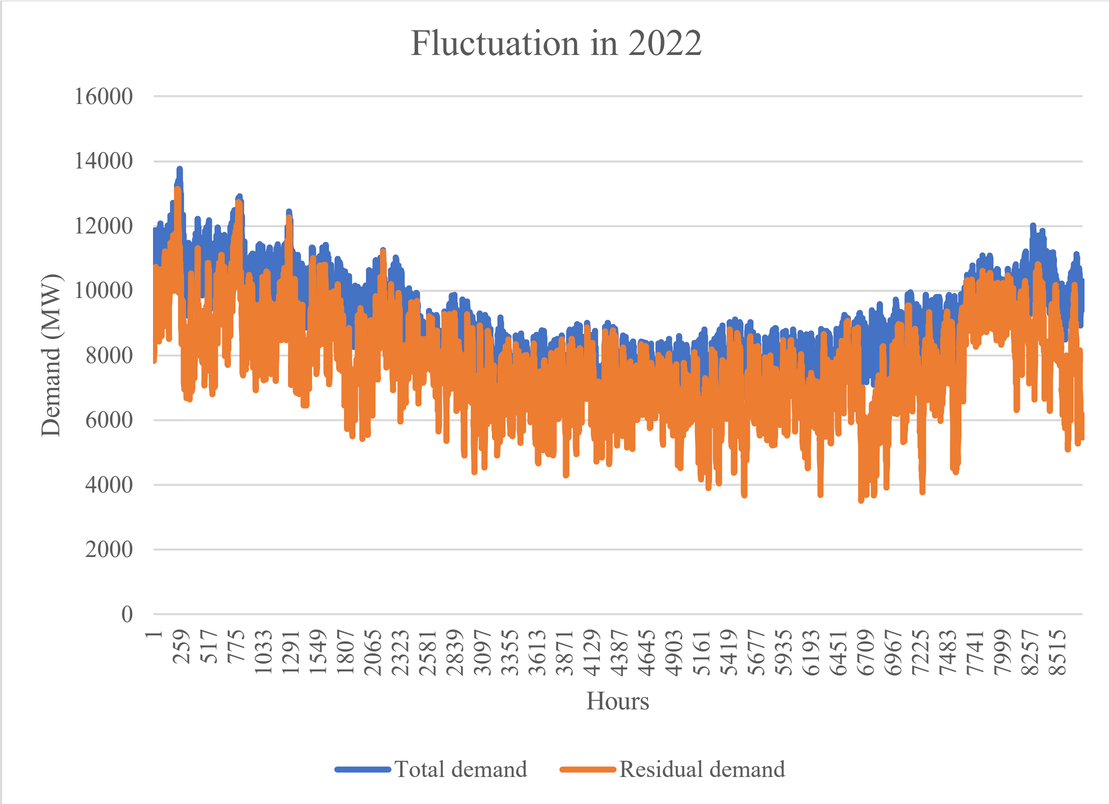

Figure 9. Fluctuation in 2022.

Electricity demand and residual demand are never steady. Demand is higher during winter than during summer. The year 2021 is less windy than 2022 and this can be seen as higher residual demand. Constant balance is needed between the input and output of electricity. The residual demand varies depending on this. Wind power is the reason for variation in the energy supply. (Clou, 2022)

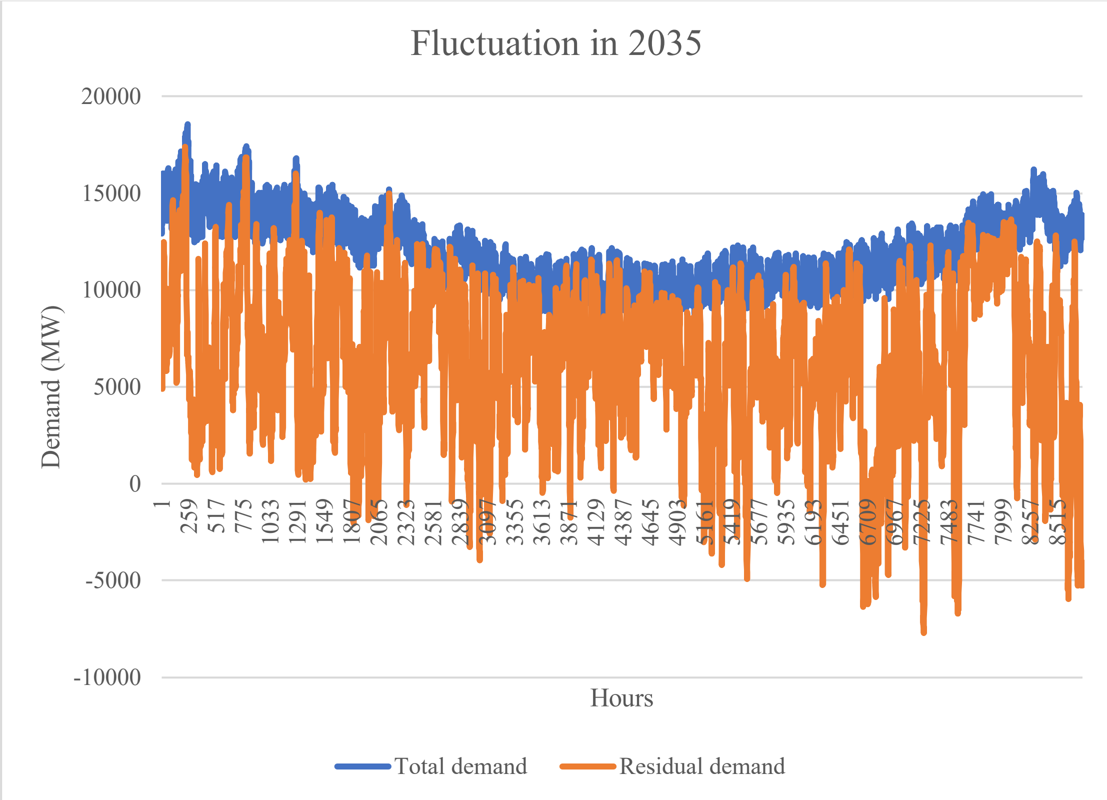

Figure 10. Fluctuation in 2035

Total demand fluctuation is more stable than residual demand fluctuation. In the graph can be seen that the residual demand reaches at certain hours zero and goes under it. When it is zero it means that only a little fraction of other sources is needed. When it is negative the whole demand is covered. Then the remaining energy produced could be stored or utilized in hydrogen production. It is interesting to see how unstable the residual demand is. High residual demand occurs when renewable production levels are low, and the demand for electricity is high. In other words, wind power production is low. Low residual demand occurs when the amount of renewable electricity is high, and the demand for electricity is low. (Do et al, 2021) It will take time until residual demand shifts below zero. (Clou, 2022)

4.2 Analysis

In this section, the electricity supply is analyzed if the production in Finland can cover the total demand in 2035. This answers the second research question. The total demand is predicted to be 18585 MW at maximum peak demand. This number is taken from the persistence curve data from figure 5 presented previously. The main idea is to find sources to cover the total demand. Besides wind power, other energy sources are needed. The selected sources are wind power, energy storage, nuclear power, import, hydropower, and gas turbines.

Finland must be made completely self-sufficient in electricity even when there is no wind and electricity is consumed in Finland at a power of 18585 MW. The maximum residual demand in 2035 is 17323 MW. This number is taken from gathered data. Wind power production is therefore 1262 MW. Energy storage systems can be assumed to cover 4000 MW of total demand (Fingrid, 2022). The number is also close to data made for modelling. During high peak storage system can be used. 13323 MW is now left to cover. There are five nuclear power plants in Finland and the total capacity is 4394 MW. The license for nuclear power plants is until 2050 and the capacity remains the same. (Fortum, 2023) Therefore, we can assume that the capacity in 2035 is the same as now. Imports can cover 5466 MW of the total demand according to Fingrid (Fingrid, 2021). The assumption is that import plays a key role in the future in covering the demand. After these sources, the total demand is 3463 MW. Hydropower can cover 3000 MW of total demand (Fingrid, 2022). Now missing capacity is 463 MW.

Gas turbines can be used to equalize during peak demand. The electricity efficiency of a gas turbine is around 40 % and in combined electricity and heat production almost 90 %. Gas turbine power plant is environmentally friendly and has small investment costs and a short construction time. (Koponen, 2014) The remaining 463 MW could be replaced with gas turbines during high peak demand. Therefore, gas turbines are most likely needed in the future to cover the small amount of demand.

Table 1. Energy sources and capacities for calculations.

Source	**Capacity (MW)**
Wind power	1262
Energy storage	4000
Nuclear power	4394
Import	5466
Hydropower	3000
Gas turbine	463
In total	**18585**

Based on these assumptions during high demand wind power production is low. To cover the demand import and nuclear power production plays a key role. Nuclear power production will stay at the same level until 2035. The amount of renewable energy is growing fast in the Nordics.

The exports are predicted to grow in 2050. In 2035 imports to Finland can be uncertain. When electricity production and imports are not enough to cover electricity consumption an electricity shortage occurs. During high peak, the maximum import in 2022 was approximately 4500 MW. (Fingrid, 2023) It is possible to import electricity from Sweden, but only if they are willing to supply it. Another line from Sweden often rather bought electricity from Finland than sold it. Electricity was sometimes imported from Estonia to Finland. Nowadays, the line is mainly used for export from Finland to Estonia. It is possible to get electricity transported from Norway. Based on these, it is uncertain to get electricity imported during high demand.

Hydropower was produced at maximum capacity during high peaks in 2022. The capacity was approximately 2300 MW. (Fingrid, 2023) In the future hydropower capacity need to grow to meet the demand. Norway has a high amount of hydropower and can export it presumably. At peak times, water can be released through turbines into a lower reservoir for hydroelectric power generation. Pumped storage systems can be effective in responding to changes in peak demand due to rapid increases or decreases. (DS New Energy, 2023) Renewable energy storage solutions enable energy storage during periods of low demand and use during periods of peak demand.

4.2.1 New investments

New investments could cover the uncertainty of electricity reliability in the future. During lower demand new energy storage systems could be charged and they could be released during higher demand. Finland is attractive for hydrogen investments and some investments are already made. A large part of the projects is still in the planning phase. The production of hydrogen will increase in Finland in the future. The hydrogen systems act as an energy storage, which enables the production of renewable energy. New nuclear power and more hydropower could also help with the reliability of electricity.

The popularity of solar energy has grown dramatically, as the prices of solar panels have dropped drastically, and the focus is on clean solutions in electricity production. The share of solar electricity in domestic electricity production is small for now, but it is growing rapidly. The use of solar electricity should be planned and scheduled as part of the entire energy system. The future is bright for solar panels in Finland.

4.3 Discussion

The energy transition creates challenges for market design and investment incentives with the security of supply. (Joskow, 2022) Weather is affecting electricity consumption. The increase in wind power variations in the Finnish electricity grid has given rise to a discussion about whether the growing wind power capacity can cause a situation in cold periods where there is not enough electricity supply. During weekends or holidays usually, renewable production is high.

The maximum residual demand is highest in 2035 and lowest in 2022. The residual demand is approximately 4000 MW higher in 2035 than in 2022 because the total demand has increased. In 2021 wind power production is low because of the not that windy year. Total demand is lower in 2022 than in 2021. Residual demand is higher in 2021 than in 2022. In 2035 other capacity is needed clearly more than now during high peak demand because wind power production is lower then.

In persistence curves, the area under curves presents the amount of other production. In 2035 the area is the biggest. 2021 has the second biggest area and 2022 the smallest. This means that other production capacity except for wind power is needed the most in 2035. In 2021 the weather was not windy and other production is needed. In 2022 wind power covered most of production and therefore the area is smallest.

Negative residual demand is bad for companies because they need to pay for production. It is good for consumers because the prices are low. During high supply hydrogen plants could be used to compensate the surplus.

The fluctuation shows how variable the need for other capacity is. During 2021 and 2022 the need for other capacity is steadier than in 2035. The need for other capacity varies a lot in 2035. Renewable energy sources can cover some of the demand in the future but for now other capacity is needed.

Residual electricity demand is a key variable for the power system as it represents the portion of the load that renewable energy production cannot meet. To address this, other energy sources, electricity imports, and energy storage capacity are needed. There are solutions to handle high residual demand. One approach is to integrate flexible demand, where industrial consumers can adjust their electricity consumption and sell excess electricity when needed. Another solution is the capacity markets, which could replace or complement the traditional energy market. (Do et al, 2021)

In addition to wind power production, the adequacy of Finland's electricity depends on the operational reliability of other power plants and the operation of electricity transmission capacity. When residual demand is high it requires flexible power plants that can help with their production by increasing it. Also, electricity imports and storage systems are needed.

5 Conclusion

In this work, an attempt has been made to approach the influence of the growth of wind power on the reliability of electricity supply from different perspectives. Although wind power is increasing, other production will be needed in the future. During high peak demand wind power production is low now and in the future. Still, wind power has the potential to be a significant contributor to the transition to a low-carbon energy system.

Total demand in 2021 was higher than in 2022. The amount of wind power was higher in 2022 because the year was windier. Electricity production capacity is needed a lot more in 2035 than now although wind power capacity has increased.

Wind power is an intermittent energy source and is weather dependent. Demand is higher during cold months and lower in mild weather. Other energy sources are needed to cover the uncertainty. Nuclear power, import, demand flexibility, and energy storage are needed in the future. Also, gas turbines are needed to cover the demand during high peaks. Finland relies on electricity imports to meet its demand. Import from other Nordic countries is important in the future. To be dependent on it can cause problems in the reliability of electricity because any disruptions in the import could potentially impact the reliability. During high peaks, it can still be a solution. Electricity demand is never steady. Consumers need electricity at various times. It is important to use electricity flexibly. Energy storage helps also to meet the demand.

The move towards renewable energy in the energy transition results in increased uncertainty and fluctuation in the electricity system. This can pose a difficulty in maintaining enough electricity generation capacity to meet demand at all times, especially during high peak periods or when renewable energy production is low. The grid must be able to adapt to wind power fluctuations. As the production from renewable sources is volatile predicting the residual demand is more challenging than predicting the total demand.

The increasing share of wind power can require adjustments in the electricity market. The market should be flexible with other electricity sources such as gas-fired plants and hydropower. This helps with the fluctuation of wind power.

The residual demand is negative for a short time of the year and is not affecting the reliability of electricity during the energy transition. The time frame is not long, but even at these times, the power grid needs power corresponding to the demand. It would not be profitable if many days would be negative.

Demand is increasing in the future and meeting this increased demand requires sufficient capacity planning. Finland has invested and needs to invest in new infrastructure to address the challenge of electricity sufficiency.

Today, electricity is a necessity, like breathing air. At every moment, electricity must be produced with at least as much power as electricity is consumed in Finland. Otherwise, the electricity grid will collapse, and it will take a lot of time to get it back up and running, and the collapse will cause great damage to Finland.

In conclusion, the increasing amount of wind power can introduce challenges to the reliability and security of electricity supply in Finland's energy system. There are however possibilities to cover the demand. Many efforts aim to ensure the security of electricity supply now and in the future. Supporting the sustainable energy system transition is important and it shows the way of action.

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