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Gradient Boosting Weather Forecasting in Finland

The Impact of Climate Change on Renewable Energy Production

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I'm grateful for my family, they have always had my back. Their faith in me kept pushing me towards the right path. Every challenge I faced, I thought I lost my way. They were there to support and bestow me with grace. Their encouragement fuelled my drive to succeed and move onward. There is no time to look behind, my only way is forward.

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ABSTRACT:

Climate change is a serious global phenomenon caused by human activities such as burning fossil fuels and deforestation, resulting in rising temperatures and more persistent weather events. Climate change has impacted Vaasa with an increase in sea levels, leading to a higher risk of flooding of coastal areas of Finland, from rising temperatures to more extreme weather events such as storms and heavy rainfall, causing damage to infrastructure and disrupting transportation and communication networks. Transition to a more sustainable future is inevitable to tackle one of the planet's biggest social challenges. This thesis aims to integrate an in-depth historical data analysis from the Vaasa area to forecast weather-dependent renewable energy generation by modeling an Artificial Intelligence (AI) machine learning technique called gradient boosting, focusing on wind, hydro, and solar generation.

Machine learning algorithms help to identify patterns and trends to forecast future energy production with the help of weather condition data. Using a gradient boosting model, a long-term time series analysis technique of climate variability has been designed to produce accurate forecasts of energy generation levels in Finland. By dividing the historical data into training and testing sets, the model can evaluate its performance and adjust its parameters. The model is taught to recognize patterns and trends. Adjustments are made to improve accuracy. It is then used to predict different future weather conditions and energy consumption levels with momentary observations. The area of research is the city of Vaasa, where En.ilmatieteenlaitos.fi historical data from 2015 to 2024 is collected to be analyzed. Forecasted data includes momentary observations of air temperature and pressure, humidity, wind speed and direction, and precipitation. The research focuses on predicting weather patterns 10 years ahead. Analysis projects evaluation of the sustainability of current renewable energy sources in Finland as well as the flexibility needs of the Transmission system operator (TSO) and Distribution system operator (DSO) more accurately in different parts of the transmission and distribution networks, related to possible voltage or thermal limit violations, frequency control needs, to improve real-time and short-term operation and operation planning of the power system. This information can help energy system operators make better decisions to guarantee sustainability, efficiency, and lower overall costs by combining AI to predict weather conditions and their impact on energy production.

The findings suggest that Finland's potential for energy independence and economic prosperity relies on the greenhouse gas effect and is possible with government initiatives to take advantage of the coming climate change in the country, mainly affecting wind, solar, and hydropower. Advanced energy storage may be the key solution when positive weather trends align with Finland's renewable energy goals. After fulfilling the maximum weather renewable output that Finland benefits from, integrated renewable systems and adaptive strategies will reduce fossil fuel dependency achieving energy independence and combating climate change impacts.

KEYWORDS: Artificial Intelligence, Battery Storage, Climate Change, Energy Independence, Gradient Boosting, Renewable Energy Sources, Time Series Analysis, Weather Forecasting

VAASAN YLIOPISTO
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TIIVISTELMÄ:

Ilmastonmuutos on vakava maailmanlaajuinen ilmiö, jonka aiheuttavat ihmisen toiminta, kuten fossiilisten polttoaineiden polttaminen ja metsien hävittäminen. Tämä johtaa lämpötilojen nousuun ja pysyvämpiin sääilmiöihin. Ilmastonmuutos voidaan havaita esimerkiksi Vaasassa merenpinnan nousuna, mikä taasen on yhteydessä suurempaan tulvariskiin rannikkoalueilla. Ilmastonmuutos näkyy myös korkeampina keskilämpötiloina sekä äärimmäisten sääilmiöiden lisääntymisenä, kuten myrskyinä ja rankkasateina. Tämän opinnäytetyön tavoitteena on integroida syvällinen historiallinen data-analyysi Vaasan alueelta säästä riippuvan uusiutuvan energiantuotannon ennustamiseksi mallintamalla hyödyntäen tekoälypohjaista koneoppimistekniikkaa, niin sanottua gradienttivahvistustekniikkaa, keskittyen tuuli-, vesi- ja aurinkoenergian tuotantoon.

Koneoppimisalgoritmien avulla on mahdollista tunnistaa malleja ja trendejä tulevan energiantuotannon ennustamiseksi sääolosuhteiden avulla. Tässä työssä on ollut tavoitteena gradienttivahvistustekniikan avulla luoda pitkän aikavälin ilmaston vaihtelun malli, joka tuottaisi ennusteita Suomen tulevaisuuden uusituvanenergiantuotannon käyttäytymisestä. Tutkimusalueena oli Vaasan seutu, josta kerättiin analysoitavaksi Ilmatieteenlaitoksen historiatiedot vuosilta 2015–2024. Ennustetiedot sisälsivät hetkellisiä havaintoja ilman lämpötilasta ja paineesta, kosteudesta, tuulen nopeudesta ja suunnasta sekä sateesta. Tämä diplomityö keskittyi säämallien ennustamiseen 10 vuotta eteenpäin. Kehitetyt tekoälypohjaiset mallit voivat mahdollisesti osaltaan auttaa siirto- ja jakeluverkonhaltijoita tekemään parempia päätöksiä tulevaisuuden uusiutuvaan energiantuotantoon pohjautuvan sähköenergiajärjestelmän tehokkuuden parantamiseksi ja kokonaiskustannusten alentamiseksi.

Löydöt osoittavat, että Suomen energia- ja taloudellinen itsenäisyys on riippuvainen kasvihuonekaasujen vaikutuksesta. Hallitusaloitteiden avulla on mahdollista hyödyntää tulevaa ilmastonmuutosta Suomessa, erityisesti tuuli-, aurinko- ja vesivoiman osalta. Energian varastoinnin edistyminen voi olla keskeinen ratkaisu, kun myönteiset säätrendeihin liittyvät tekijät sopivat yhteen Suomen uusiutuvan energian tavoitteiden kanssa. Kun Suomen uusiutuvan energiantuotannon määrä on saavutettu, integroidut uusiutuvat järjestelmät ja sopeutumisstrategiat vähentävät fossiilisten polttoaineiden riippuvuutta, edistäen energia- ja ilmastotavoitteiden saavuttamista.

AVAINSANAT: Tekoäly, ilmastonmuutos, uusiutuvat energialähteet, sääennustus, aikasarja-analyysi, gradientin vahvistus

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Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
ARIMA	AutoRegressive Integrated Moving Average
BESS	Battery Energy Storage System
CHP	Combined Heat and Power
CNN	Convolutional Neural Network
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electrical Vehicle
GDP	Gross Domestic Product
IES	Integrated Energy Systems
ISO	Independent System Operator
LSTM	Long Short-Term Memory

ML	Machine Learning
NWP	Numerical Weather Prediction
NAO	North Atlantic Oscillation
PV	Photovoltaic
RES	Renewable Energy Sources
RNN	Recurrent Neural Network
RTO	Regional Transmission Organization
SARIMA	Seasonal AutoRegressive Integrated Moving Average
STM	Short-Term Memory
TJ	Terajoule
TOU	Time Of Use
TSO	Transmission System Operator
TWh	Terawatt-hour

1 Introduction

The increasing availability of renewable energy sources (RES) around the globe provides cities with the potential to transform into more sustainable energy systems. Vaasa, one of Finland’s coastal cities, is well-positioned to take advantage of trends in renewable energy production due to its location in the Baltic Sea (Bruun, 2024). The city has made a decisive step in incorporating RES, where the notable contributor is wind power. Finland keeps investing in renewable energy infrastructures as it has proven to be one of the opportunistic leaders in a sustainable energy economy, by reducing carbon emissions, enhancing security, creating economic opportunities for its people, and serving as a model for other countries.

Weather forecasting has been revolutionized with artificial intelligence (AI), which provides faster and more accurate predictions, advances different industries, and benefits energy production and consumption. The large amount of data that can be processed enables reliable weather forecasting, which is especially important for energy companies that can adjust their operations based on changing weather conditions. With the help of AI, these companies can predict a sharp decline in temperature and meet the customer demand for energy production for heating. This stabilizes energy supply and reduces power outages due to fast response (Cepsa, 2024; Finnish Meteorogical Institute, 2024).

Vaasa's weather experiences fluctuations in winter and summer, where it is classified as a maritime climate (Finnish Meteorological Institute, 2024). Precipitation is highest in summer and remains moderate the whole year. With the climate changing, recurring weather events such as storms, floods, heat waves, and droughts are being altered. These events not only cause property damage, but also result in productivity losses and affect the human way of living (Newman & Noy, 2023; Meteoblue, 2024). Goods and services are at risk due to these altered conditions, for example, heatwaves reduce production in an environment of increased temperature and humidity, and storms could disrupt supply chains and transportation. The energy sector is particularly vulnerable in response to these changes as it is a key driver of economic growth. If the weather

fluctuates negatively, it can impact energy production, leading to power outages and rising costs (Future Mobility Finland, 2021).
The city of Vaasa aims to become carbon neutral by 2030. According to Nebiyu Girgibo at the University of Vaasa, climate doesn't necessarily affect the environment negatively. The study conducted in the Kvarken Archipelago, Finland's only Natural World Heritage Site near Vaasa, indicates that water temperature rise increases ground heat energy production during the summer, while in the winter it is reduced (Future Mobility Finland, 2021; Girgibo, 2023).

For the past decade, the global mean temperature and sea level have increased, while consistent spatial variations in global precipitation are becoming more evident, along with more frequent extreme weather events in various countries. It is essential to transition from fossil fuels to only renewable energy sources, such as hydro power, wind power, and solar electricity, to promote environmental sustainability and mitigate climate change. However, fossil fuels can also play a pivotal role in driving changes in the Finnish climate to enhance renewable energy production (International Energy Agency, 2021). Forecasting has the potential to lower the prices of energy production significantly. Companies utilize this to focus more on customer services and prevent energy losses that contribute to unnecessary greenhouse emissions, which would require relying on fossil fuels for the lost energy to supply the demand (Cohen et al., 2019). Energy companies that use machine learning algorithms to train their AI systems produce accurate forecast data to inform customers' long-term investment decisions. Forecasting is essential because it facilitates the transition from previously unreliable options and moves towards building more dependable alternatives during periods of high demand. Building more renewable energy infrastructures minimizes reliance on fossil fuels, leading towards an attractive trend with less overall cost and high energy production, improving resilience and resulting in energy independence (Hosein et al., 2020; Matos et al., 2024). Homeowners can use the forecast data to charge their own photovoltaic (PV) systems at home during blackouts when the grid is stressed, ensuring uninterrupted electricity supply at no additional cost from the company (Esfandyari et al., 2019).

AI automates data processing, enabling interpretation, analysis, and weather information communication, where experts can implement actionable solutions for the impacts of weather conditions, give recommendations to different stakeholders, and improve resource allocations. Energy companies would be able to reduce costs and increase energy production while contributing to keeping the climate sustainable (The Weather Company, 2023). The excess energy generated during peak production times is stored in energy storage systems, such as batteries, reducing the need for fossil fuels accordingly. There will be fewer carbon footprints and environmental impacts, and AI-driven weather forecasting can contribute to that (Katz, 2020). With the help of AI algorithms, energy companies can optimize solar panel arrays for maximum energy generation during adverse weather conditions. When it is used to predict times of high wind speed, they can calibrate wind turbines to generate more electricity (Bezrukov, 2024; Alves et al., 2023). Outside of energy generation, AI algorithms can help reduce energy consumption by preparing for times of high demand. The benefit is having a dynamic choice to reduce energy waste and strain on energy grids (Mystakidis et al., 2024). For example, AI forecasts heatwaves, and the company adjusts energy distribution to ensure sufficient supply to meet the demand for cooling (Emb Global, 2024).

The electricity market comprises a spectrum of trading methods from electricity production to consumer services, harnessing technology to enhance the effectiveness of electricity generation and distribution, and minimize consumption. The optimization contributes to promoting renewable energy businesses in Finland, while the infrastructure development intends to serve the rising demand for electricity while reducing greenhouse gases. Through competitive auctions and bidding, service providers may balance the supply and demand dynamics of energy pricing by influencing the selling and buying power within the market. For electricity consumers, real-time monitoring of their charging becomes essential, particularly those utilizing electric vehicles (EVs) for cost savings (EPA, 2024; Morstyn et al., 2018). Exploring Machine learning as a key tool for managing energy features forecasting supply and demand across different structures and frameworks of the electricity market. It also considers factors related to energy system operators, such as Transmission System Operators (TSOs), Distribution System Operators (DSOs), and Distributed Energy Resources (DERs), which play a prevalent role in managing grid stability. These entities operate in various sectors (buildings, industries, transportation) utilizing electricity, heat, and fuel. Renewable energy sources, energy storage technologies, and smart grid technologies with demand management strategies minimize costs and greenhouse emissions while enabling demand response to match energy supply and optimize production across different sources (Reilly, 2024; Reinhold, 2023; Hämmäinen, 2022; Cummins, 2021; Abdullah et al., 2021).

This thesis focuses on gradient-boosting weather forecasting for renewable energy generation in Finland. It will primarily involve collecting historical weather data from the city of Vaasa and integrating time series analysis and machine learning techniques to forecast future weather conditions. Time series is a well-known technique used in multiple fields such as sales and finance, weather forecasting, and energy consumption. It is useful when there is a clear relationship between past and future and involves identifying patterns like seasonality and trends (Yakymic, 2021). Weather conditions are researched by conducting long-term forecasts of air temperature, wind speed, precipitation, and cloud cover in months, analyzing each season. Utilizing the machine learning method of gradient boosting, the accuracy of current RES, such as wind, solar, and hydropower, can be compared with Finland's zero-emission goals. The simulation result analysis concludes with a rather interesting outcome that contradicts Finnish government initiatives before 2035. The thesis tackles a key question regarding the issue posed by climate change: is the constantly changing weather in Finland resulting in better or worse energy production compared to the past?

2 Background of the study

When climate is discussed as a term, it refers to long-term patterns of temperatures, precipitation, humidity, and wind patterns occurring in a region, typically known as weather conditions that prevail in an area over an extended period. Generally, they last for 30 or more years, and the climate is determined by the factors of the Earth's distance from the sun, the tilt of the Earth's axis, and its land distribution, as well as the waters. Climate shouldn't be confused with the weather, which refers to short-term conditions of the atmosphere, usually on a day-to-day basis (Wikipedia, 2024).

On the other hand, climate change refers to decades of significant shifts in global or regional patterns that are changed by resulting natural processes, such as volcanic eruptions, solar radiation, and human activities. The main concern in today's world is the impact of human behavior of releasing greenhouse gases from burning fossil fuels, deforestation, and industrial processes, which have led to global warming and other climate changes (Wikipedia, 2024).

2.1 Key Concepts and Theories

2.1.1 Renewable Energy Sources (RES)

Natural processes that are responsible for continually replenishing are called renewable energy sources. Wind power, Hydropower, and solar power are Vaasa's primary sources. Wind power uses wind turbines to make use of wind to generate energy. Photovoltaic (PV) panels use light or sunlight to convert it into energy. Hydropower uses dams to harness the water flow, turning it into electricity. They all have weather conditions with a common denominator and would depend on how much energy is produced on a bad or good day (Twidell & Weir, 2021).

2.1.2 Climate and Weather Patterns

Every location, whether a country, city, or town, is classified under a climate category. There are six classifications of climate regions (Wikipedia, 2024).

Tropical climate: Warm temperature with frequent heavy rainfall near the equator throughout the year.

Temperate climate: Medium temperature with fluctuating precipitation (rain, snow, Ice, or hail), found in the mid-latitudes.

Continental climate: Big fluctuations in temperature with low precipitation, found near the poles.

Polar climate: Glacial temperature, due to altitude, occurs in the mountainous area.

Highland climate: Cool temperature, occurring in rocky or hilly areas.

Oceanic climate: Medium temperatures around the year with high precipitation. Small fluctuations in summer and winter. Found in mid-latitudes of the western coasts of continents.

Vaasa city belongs to the Oceanic category, more commonly known as the maritime climate, where the Baltic Sea affects weather patterns like storms, heatwaves, and dry periods.

Understanding these patterns is vital for forecasting energy production and building suitable infrastructure (Bruun, 2024).

2.1.3 Traditional weather forecasting vs non-traditional weather forecasting

Traditional weather patterns are being changed by climate change, which has led to repeated and extreme weather events.

Non-technological forecasting: Observations of weather event trends, and methods used to forecast that arise in specific regions through generations, like seasonal changes (temperature), prevailing winds (fast-moving air currents and wind direction), coastal influences (fogginess), thunderstorm patterns, and rainfall (Ignitia, 2024; Tahiluddin et al., 2023).

Traditional weather forecasting observations:

- Hair-like clouds indicate incoming rain or clouds.
- Wind blowing from the south indicates incoming typhoons or floods.
- Warm temperatures at nighttime indicate upcoming rain in a day or two.
- Fog indicates good weather
- Observing ocean waves helps understand weather patterns.
- Animal behaviour, such as birds migrating.
- Sunrise and sunset time changes indicate weather changes (Malchoff, 2024; Tahiluddin et al., 2023).

Non-traditional weather forecast: Observations of weather event trends with the help of weather stations and satellites, and computational forecast methods, incorporating mathematical analysis, AI, and machine learning techniques to improve accuracy and speed. Statistical models are used to recognize patterns of historical data.

Leading forecasting state-of-the-art AI models like Google's Graphcast predict up to 10 days in advance using the cause-and-effect historical data method. Google has developed Nowcasting, a localized short-time model, which provides 90 minutes ahead (Bassetti, 2024).

Non-traditional forecasting is an advanced method for predicting short and long-term events. Traditional methods have only been able to predict short-term time ranges. It cannot be used to predict every event, unlike non-traditional forecasting, where AI would advance learning from each changing event. Although AI is involved, long-term does not imply better results. Research shows short-term forecasting is more accurate than long-term forecasting (The Weather Company, 2023).

2.1.4 Impacts of climate

Climate change is rooted in building carbon emissions to the atmosphere, primarily due to the burning of fossil fuels and deforestation. The heat produced is trapped by the gas in the environment, affecting the economy and human quality of life. A warmer Earth leads to an increase in sea level due to the melting ice and precipitation patterns. This phenomenon increases flooding in communities in coastal regions (Hastings Borough Council, 2024). Increased temperature also leads to water evaporation, leading to less water availability. This also affects the hydro production for energy.

The most frequent weather events are extreme weather conditions like heat waves, droughts, and floods, damaging the ecosystem, infrastructures like roads, buildings, water systems, and human health (United States Environmental Protection Agency, 2024). For example, heatwaves decrease the efficiency of power plants. Storms can disrupt supply chains and transmission lines, leading to power outages and disruptions in energy supply. That is why weather forecasting can help prevent the risks by adapting strategies ahead of time (iGPS, 2024).

Air quality issues leading to health impacts, wildfires, migration, and agricultural food security are all consequences of the changing climate, and they are costly when repairing the damages and addressing disruptions to daily life. When the weather gets hotter, people demand more cooling. Higher energy consumption means more strain on the energy systems. There is also a reduction in energy efficiency in these times due to the system's inability to keep up with the demand (Environmental Protection Agency, 2024).

More demand equals raising energy prices for customers. When customer demand must be met, backup energy production is required beyond renewable energy sources. This includes fossil fuel combustion, which leads to emissions (United States Environmental Protection Agency, 2024; Energy.gov, 2013).

2.2 Electricity Market

The electricity market involves trading of electricity from generation to retail with services. Modern solutions using technology to optimize smart electricity market mechanisms for maximum electricity generation, distribution, and consumption have contributed to the energy business. In the context of renewable energy sources, infrastructure has been utilized to accommodate the growing demand for electricity while reducing emissions.

Service providers have transactions based on a balanced supply and demand, buying and selling according to bids in the energy market auction. Different bidding methods decide how much energy costs within the specified market. Real-time pricing is essential for electricity buyers. These buyers could be, for example, electric vehicle (EV) owners who need to charge their cars during off-peak hours. This way, they can save money on electricity (Morstyn et al., 2018).

The next section will examine the types and structures of electricity markets, emphasizing factors related to energy system operators.

2.2.1 Electricity market types

Wholesale electricity markets are traditionally sold among generators, resellers, and utilities as either independent system operators (ISO) or regional transmission organizations (RTO) to run a competitive market in a region for independent power producers to sell electricity. The retail market provides electricity directly to consumers, purchased through their local utility grid; consumers can choose their electricity suppliers (EPA, 2024).

Figure 1 represents a market timeframe overview of the market type and function available for purchase by buyers. The transmission system operator (TSO) balances the energy capacity obtained and paid for to make it available for use or consumption.

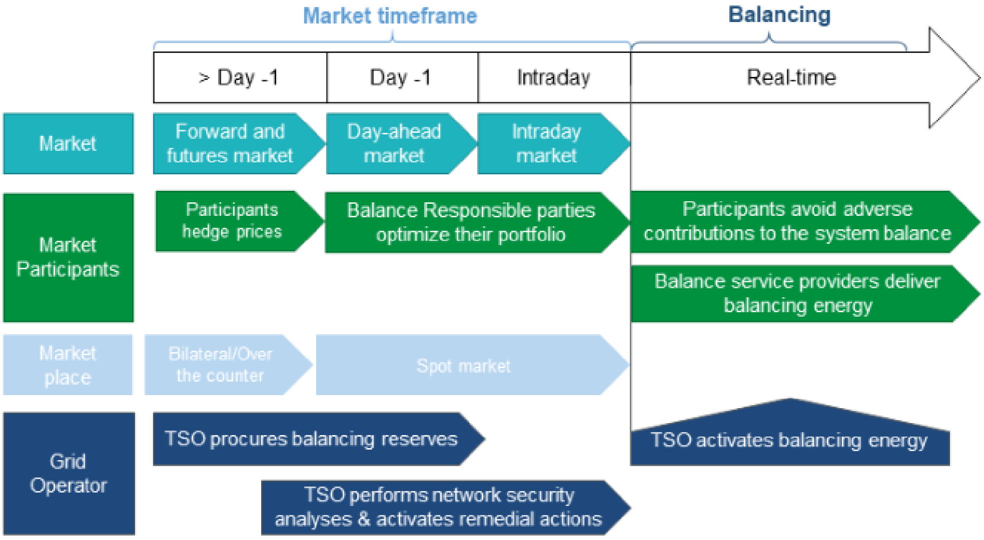


Figure 1. The different market types (Tennet, 2024)

Forward and futures market: Hedge prices are where the companies trade futures contracts, where the buying/selling of future electricity focuses on the coming months and years (EPA, 2024). This essentially means that participants hedge against price volatility in the spot market. This market has a risk. It is used to lock future electricity prices and helps companies to manage and stop market fluctuations. Essentially, it provides a stable price of electricity. The difference between forward and future markets is that forwards are over-the-counter bilateral contracts with more customizable contract terms. The future market is standardized completely (Tennet, 2024).

Day-ahead markets: A contract between two parties a day or a few days before the electricity is delivered, where the buyer can decide the consumption bargain on demand. This helps predict lower expenses for electricity during consumption when arranging, for example, electric vehicle charging in the off-peak hours (Tennet, 2024; Al-Gabalawy, 2021).

Spot market: A market where the buyer can purchase up to five minutes before the electricity is delivered, as it helps manage the fast-changing prices based on supply and demand. Participants include generators, electricity retailers, and transmission operators.

Weather conditions, fuel prices, and network limitations affect fluctuating prices (Tennet, 2024; Al-Gabalawy, 2021).

Reserve markets: Operated by the Transmission System Operator (TSO) in real-time to balance the grid and keep grid stability by setting aside a certain amount of electricity capacity, frequency containment, and restoration reserves in case of unexpected shortages. This is important, for example, for electric vehicle users who otherwise would become expensive with extensive charging. In power markets, the energy sources are sent to the grid starting with the lowest operating cost, and it goes up until enough demanded energy is produced. The economic resources are prioritized, and consumers benefit from their expenses being cut when there is robust production of renewable energy sources. When the supply and demand are equal, it is called the ''clearing price'' (Tennet, 2024; Al-Gabalawy, 2021).

Intraday market: Trading electricity within the same day to profit from short-term price movements, allowing large consumers, power generators, and energy traders to regulate their position in real-time to balance the grid. The market is very volatile, and it is beneficial for traders. It improves system efficiency as participants respond to the changing supply/demand as trading happens directly between market participants, but price fluctuations occur in real-time in these conditions (Tennet, 2024).

2.2.2 Integrated Energy Systems

Integrated energy systems (IES) exist to operate different buildings, industries, and transportation using energy systems like electricity, heat, and fuel to sustain energy services. ''It links energy-consuming sectors to the power grid to optimize the unity between the production of energy and use of energy''- IES can be characterized by linking and operating different energy systems to minimize costs and greenhouse emissions, by integrating renewable energy sources, as they also provide a decentralized source of power. They combine renewable energy sources with energy storage technologies, smart grid technologies, and demand management strategies (Danfoss, 2024). The energy systems produce solar, wind, hydro, and biofuels, converting them into electricity, thermal, and hydrogen. Depending on the season, a single renewable energy source producer can provide multiple forms of energy, such as heating, cooling, electricity, steam, and water purification—for example, solar power in the summer to lower the costs. Integrated energy systems support these services and enable a flexible demand response to match the energy supply. As seen in Figure 2, Transmission system operators (TSO) and distribution system operators (DSO) operate through buildings from cities to regions, coordinating the Integrated energy systems (Danfoss, 2024; Berkeley Lab, 2024).

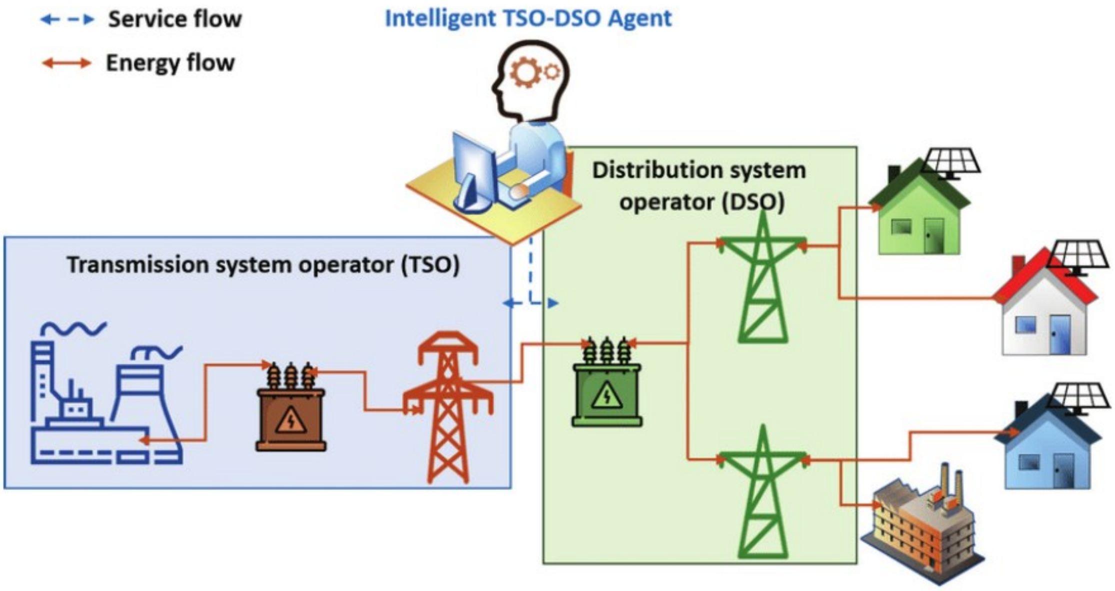


Figure 2. TSO & DSO coordination with Intelligent agents for a stable energy market (Munir et al., 2020)

Transmission System Operators: They control and transmit electricity from generation plants through power grids to the distribution operators. They are responsible for delivering sufficient energy supply continuously autonomously from electricity production to sales and tend to focus on minimizing costs. They hold operations and maintenance and try to maintain an uninterrupted flow of electricity from generators to DSOs and end consumers. Some of TSO's key roles are to reserve extra energy in storage and forward it, restore an electric power station or grid to operate after a blackout by connecting to more generators, and measure frequency responses of system processes to adjust communication networks (GridX, 2024). TSO monitors the electricity market by balancing supply and demand in real-time and expanding infrastructure to meet future needs (Tennet, 2024).

Distribution System Operators: These operators get their electricity from TSO to regions or local areas where they manage and operate. DSO manages and operates the power grid, oversees the transmission, and delivers electricity to end consumers. While TSO operates the high voltage distribution grid (power plants), which travel long distances, DSO operates and maintains the low voltage distribution grid, including power lines, substations, and transformers that deliver electricity to homes or businesses. Aside from having a crucial role in integrating renewable energy sources into the grid, the DSO also has key roles in acquiring new customers and distributing energy sources to the distribution grid. These include solar, wind, and batteries. DSO works in real-time to manage electricity supply and provides services such as voltage support, peak load management, and help for jams (Reinhold, 2023). DSO cooperates with TSO to adjust electricity flow across each interface and uses net load forecasting on the distribution grid to balance the supply/demand. DSO also provides data and forecasts to participants in the electricity market and improves the planning to develop new business models for Distributed energy resources (GridX, 2024; Current, 2024).

The coordination between TSO-DSO: They partner to purchase grid services from aggregators, suppliers, and consumers and integrate DER into the grid. TSO and DSO use resources to abstain from altercations between their needs by cooperating through integrated markets with the help of digitalization and data sharing to ensure high DER penetration (success of distributed energy resources) (GridX, 2024). They work together to fix network constraints, for example, when there are potential bottlenecks, TSO and DSO can adjust the output (Reinhold, 2023).

Distributed energy resources (DER): Demand response or small power generators close to load centers operate by being connected to larger power grids that TSO/DSO manage. They benefit by reducing electricity costs for individual users. They have low carbon emissions. DERs are wind turbines, battery energy storage systems (BESS), natural gas generators, microturbines, heat and power systems, fuel cells, biomass generators, hydropower, and electric vehicle (EV) applications (Cummins, 2021).

Demand response energy optimization: The electrical grid gives price signals to the consumer, where they can adjust their electricity usage to help balance the supply and demand. Consumers can manage their electricity usage manually or automatically with the help of smart devices. It is helpful during peak times of the grid being under stress, when the price and demand are the highest, to shift to off-peak hours when the price and demand are the lowest. Consumers would reduce electricity usage when it is not needed. Therefore, the capacity does not need to be increased, and it helps maintain the efficiency of electricity systems (Hämmäinen, 2022).

Aggregators: Aggregators work with both TSO and DSO to provide grid services. They combine various distributed energy resources of the household or company, such as solar panels, batteries, and EVs, to integrate into the grid to get the desired effect on the power systems, as seen in Figure 3 (GridX, 2024).

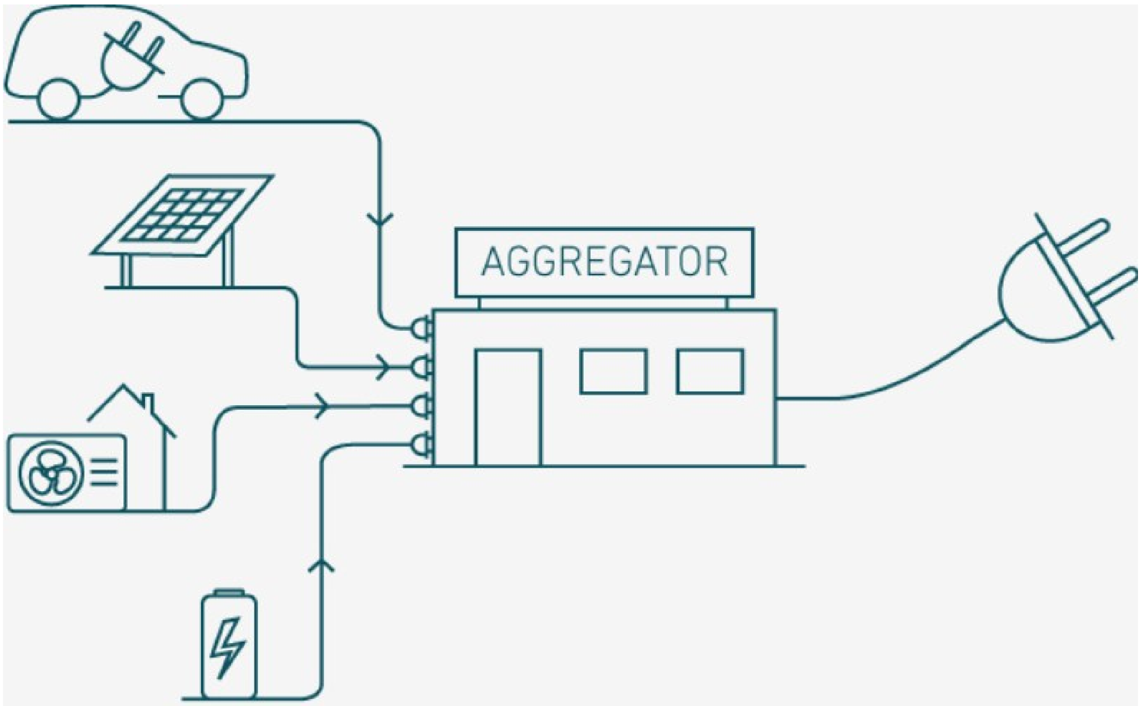


Figure 3. An aggregator is a person or business that combines multiple DERs (ENERGINET, 2024)

When an individual tries to manage their energy, they require external support from an aggregator. They help combine and optimize resources for efficient and sustainable electricity use. Aggregators (companies) help businesses or individuals adjust specific times to sell their electricity usage to fit the electricity market demand. For example, consumers with heating or cooling systems or household smart appliances can join the demand response program through an aggregator and sell their electricity usage to balance the supply/demand of the electricity market. This means that they get payments from the aggregator to reduce electricity usage or when they change to peak hours. When the price is high, aggregators disconnect the consumer’s demand, and when the price is low, they increase the demand, better known as the ‘’downward and upward regulation of demand’’ (ENERGINET, 2024).

2.2.3 Machine learning for managing energy

Machine learning (ML) can be used to forecast supply and demand in addition to storing energy in battery storage systems. This is accomplished by analyzing trends and patterns of energy produced and consumed based on the behavior of renewable energy sources. It is a method used to sustain carbon-free conditions as much as possible while avoiding alternative solutions that rely on emissive producers and maintaining cost-effectiveness. ML relies on historical weather data instead of physical equations. For example, forecast models can predict weather conditions (temperature, humidity, wind, pressure, precipitation) and sudden events through the use of data collected from satellite imagery and sensor data, giving real-time data such as solar irradiance to adjust charging sessions of a household in real-time as well as correlating with the predictions to refine to the use of renewable energy, while modifying charging rates by the help of ML to prevent grid surcharge (Reilly, 2024; Shin et al., 2020). Machine learning incorporates inductive reasoning with forecast models like deep neural networks to learn patterns from current climate and future conditions from large datasets. These are called reinforcement learning models that adapt to changing weather patterns cumulatively to predict short-term or long-term. They can be pre-trained using limited amounts of data, such as accurately forecasting long-term solar irradiance (Joen & Kim, 2023). Control techniques that learn from past actions can also be integrated to improve decision-making in the distribution and consumption of energy. When forecasting renewable energy for energy systems, it is crucial to use these solutions to manage consumers (households and businesses) and electrical grids that need to charge efficiently through naturally unpredictable weather. Employing machine learning to anticipate fluctuations and change consumption patterns is beneficial, as it improves company services, enhances customer quality of life and trust, and creates an opportunity to advance the renewable energy-only future we aspire to (Abdullah et al., 2021).

The following reasons dive into why machine learning is essential for demand response and smart electricity use for households:

Algorithms to optimize the charging process: Cutting consumer bills is minimized with adaptive smart optimal charging time algorithms. Integrated weather forecasting data can anticipate spikes in demand due to extreme weather, then schedule EV charging schedules to reduce dependency on non-renewable energy sources and manage grid load. The vital role is shifting charging times from lower demands and when there is excess renewable energy (Lan et al., 2021).

Time series algorithms in the forecast: A time series is a cycle with recurring intervals and recorded data points, each representing a value of a specific instance that reflects the progress of an identified irregularity. These moments recognize patterns of season and trends as they cycle through behaviors over a timeframe. Time series algorithms are essential for weather forecasting, as they analyze historical data and predict possible changes in future conditions. The AutoRegressive Integrated Moving Average (ARIMA) model is a widely recognized technique for capturing linear patterns in data. Long Short-Term Memory (LSTM) is a deep learning method capable of handling non-linear patterns. According to Hewage et al. (2020), these models progressively improve the accuracy of weather predictions by taking advantage of substantial historical datasets like temperature, humidity, and wind speed (Hewage et al., 2020).

Renewable energy source integration: The randomness of the weather makes it hard for RES to be incorporated into the grid, where machine learning algorithms can operate the grid effectively and plan for energy storage and distribution. The ML can forecast using historical data and weather estimations and then forward it to the grid. For example, the ML model can detect that the cloud cover is escalating following the decrease in solar power production and balances the electrical grid by adjusting the charging schedules (Shin et al., 2020).

Grid stability augmentation: Grid stability means keeping a constant voltage and frequency to meet the demand for electricity users. A critical part of power system operations is where serious consequences can lead to equipment damage and blackouts. Stability means that electricity is supplied despite the disturbances or fluctuations in the system. Machine learning helps provide data about different sources and manage energy flow output of energy consumption with historical energy data usage, learning consumption patterns, renewable energy generation predictions, and, for example, real-time electrical vehicle battery conditions. According to Mololoth et al. (2023), with the help of sensor data analysis, grid failures can be predicted and allow dynamic maintenance, reducing the risk of network instability (Mololoth et al., 2023).

3 Literature Review

The study by Teixeira et al. (2024) describes weather forecasting as predicting and mitigating causes of weather conditions or preparing to adjust accordingly as much as possible to benefit from the outcome. To minimize environmental impacts and reduce electricity costs and losses, it is crucial to understand and accurately predict weather variables to optimize renewable energy resource production (Teixeira et al., 2020).

Scholars have found various ways to approach the goal of utilizing cost-saving advantages for energy consumers from price fluctuations to weather conditions (Foster & Caramanis, 2013).

Smart grid data helps energy consumers save money, such as when a user charges their electric vehicle based on battery levels or departure time. They might choose to charge only when their battery is low, or they can schedule charging for when they need to use the vehicle and take advantage of lower electricity rates. This data gives control of their car during electricity price changes.

To manage supply and demand grid operations, weather forecasts can predict, for instance, solar radiation and wind speeds required to determine the power output from solar panels and wind turbines. Weather forecasting aids in the maintenance of infrastructures and strategic planning by anticipating extreme weather conditions. Measures like this are how energy providers can ensure continuous energy production during blackouts. With strategic planning, grid operators can plan for storage solutions and use backup power sources to maintain energy supply (Teixeira et al., 2020).

The forecasts become more accurate the closer the results are to the actual date. Despite technological advancements, we may never be able to predict the weather with 100% accuracy. To predict the weather with absolute certainty, we need to know the constantly changing position and movement of all the molecular particles, which is currently impossible even for the best computers (Stolzenburg et al., 2023). According to mathematician and meteorologist Edward Lorenz, this is one of the broader concepts tied to the chaos theory butterfly effect that demonstrates even the smallest differences in the primary conditions in weather simulation models lead to a completely different outcome and present a challenge to long-term weather predictions, being exceptionally sensitive to accurate forecasts. Accurate predictions depend on accurate information, and the farther out you are, the higher the chances that information can change. For better accuracy, it should be held off as close to the actual event (Foster & Caramanis, 2013). Therefore, short-term weather forecasts are preferable. Methods of accurately predicting sudden changes in the atmosphere are the need to use historical data to forecast. Just like how weather forecasting is dependent on time close or further away from the actual event, it may be so that the historical data to teach the machine learning system might not always be helpful, because the historical data itself might not always be accurate. Historical data that can be incomplete or inaccurate impacts the ability to model future conditions accurately. As a result, weather forecasting algorithms will be less reliable, making it challenging to capture complex weather variables (Teixeira et al., 2020).

Karapanagiotidis (2012) and Chen et al. (2023) discuss that time series methods, also categorized as traditional statistical approaches, have been widely used in many fields, primarily in weather forecasting with the help of machine learning techniques to predict future phenomena based on historical data. The idea behind this method is to use past event analysis to predict future ones, typically specifying the dynamic relationship between variables. The models used in the time series forecasting are based on regression analysis. The relationship between the dependent variable and independent variables is defined as the linear parametric relationship, meaning that the relationship between the irregularities is statistically independent and is limited by how the linearity and stationarity (mean and variance) are assumed, which may not be accurate when dealing with weather patterns that show non-linear and non-stationary behavior. Statistical properties of data that change over time because of climate change, long-term trends, and seasonal variation are called non-stationary, which weather patterns often are, therefore, it is hard to adapt them into accurate predictions (Chen et al., 2023; Karapanagiotidis, 2012). Weather patterns are non-linear, and traditional models use linear models that might not express non-linearities well. Regardless of the advancements in time series methods, the limitations in capturing multi-time scale weather patterns have shown to be particularly challenging for traditional methods, often in the scales from daily, seasonal, and long-term trends. Accurate weather forecasting still relies on high-quality data from various satellite observatories and weather stations rather than one climate model, which might limit methods like artificial neural networks (ANN). Data mining is a machine learning technique that uses algorithms such as ANN to analyze large datasets and extract purposeful patterns showing promising results in understanding weather forecasts, such as rainfall and thunderstorm predictions (Mishra & Jain, 2014).

Karapanagiotidis (2012) and Chen, et al. (2023) emphasize that even if advanced time series models are used that incorporate machine learning (ML) techniques, they are computationally demanding. This way, the exploration of complexities of multi-time scale weather patterns can be captured, leading to improved accuracy and reliability of weather forecasting. Accurate weather forecasting still relies on high-quality data from multiple satellite observatories and weather stations rather than one climate model, which might limit methods like ANN (Chen et al., 2023). To address these limitations, time series need to be developed with AI that can leverage the strengths of both traditional and machine learning (ML) techniques like deep learning models to bring more flexibility and robustness (Chen et al., 2023; Karapanagiotidis, 2012).

Current research emphasizes how significant time series weather forecasting is, centered on machine learning (ML) techniques. Researchers are finding ways to combine ML models into traditional weather prediction systems to ensure forecasting becomes effective and reliable. Computational demands are traditionally extensive (Deutscher Wetterdienst, 2025; Neumann et al., 2023).

Research has enhanced accuracy and reduced these demands by associating numerical weather predictions (NWP) models —mathematical models derived from global reanalysis data simulating the atmosphere's physics, including temperature, pressure, humidity, wind speed, and direction, among other relevant variables, to compare with actual weather observations to assess their accuracy (Deutscher Wetterdienst, 2025; Neumann et al., 2023).

Aside from GraphCast, a forecasting model developed by Google, models like FourCastNet by Google and PanguWeather by Microsoft are trained to reanalyze datasets that predict atmospheric variables at multiple time steps and reduce resources and time in computational forecast generation with AI. These models have been developed and highlighted, showing the potential of ML. Researchers concurred that AI holds significant potential but acknowledged that fundamental advancements are required before AI-based techniques have the potential to surpass NWP (Cheon et al., 2024; ECMWF, 2024; Neumann et al., 2023).

They all leverage data from the European Center for Medium-Range Weather Forecasts (ECMWF), in their training process. The models did not surpass the organization’s NWP-integrated forecast system's accuracy, but excelled in speed. ECMWF is an intergovernmental organization producing and disseminating NWPs, holding the largest forecast archive of data (ECMWF, 2024).

Current weather forecasts rely on the data from NWP models to learn and make predictions, but still need to be checked regularly to determine whether the results produced by these models are realistic and to evaluate the physical weather principles (ECMWF, 2024).

Researchers have refined the accuracy of wind and solar power with time series forecasting in energy for electrical demand instead of using raw weather data by applying weather data transformations such as statistical features, dimensionality reduction, clustering, or autoencoders to station or grid-based weather data. So far, statistical and dimensionality reduction are the most effective. Statistical transformation measures simplify the average value of the dataset, the amount of variation in the dataset, and the smallest and largest values in the dataset. It keeps the key aspects of the inputs without preserving raw data. The goal of dimensionality reduction is to decrease the number of inputs that make the data smaller by removing irrelevant data points to improve the model's performance. How the data is used impacts how accurate forecasting is. Wind power forecasting is more effective when applying transformations to station-based data, while solar power forecasts have improved results with grid-based weather data (Cheon et al., 2024; ECMWF, 2024; Neumann et al., 2023).

Although there have been advancements, ML-based forecasting often has systematic errors over Europe during the summer with cold distortions or geopotential heights. Therefore, for consistency and to provide deeper insight into model performances, conditional verification is required to refine this research, focusing on detailed physical operations and links between variables in order to mitigate the biases (Bouallègue et al., 2024).

3.1 Why has Finland's climate changed?

3.1.1 Impacts of climate

The main driver for Finland's changing climate is greenhouse gases (GHGs), a sign leading to global warming. The greenhouse gases in the atmosphere have amplified the greenhouse effect, trapped more heat, and increased global temperatures. These global models show the accumulated carbon dioxide (Räisänen, 2019).

Evidence suggests that Finland and many other northern regions are experiencing intense warming. The Representative Concentration Pathway (RCP) shows that Finland will continue to get warmer in the next few decades, especially in the winter, because of the increased radiation. RCPs are climate change scenarios that project future greenhouse gas concentrations. Because of greenhouse gases, there is an imbalance between solar radiation and outgoing thermal radiation (Räisänen, 2019).

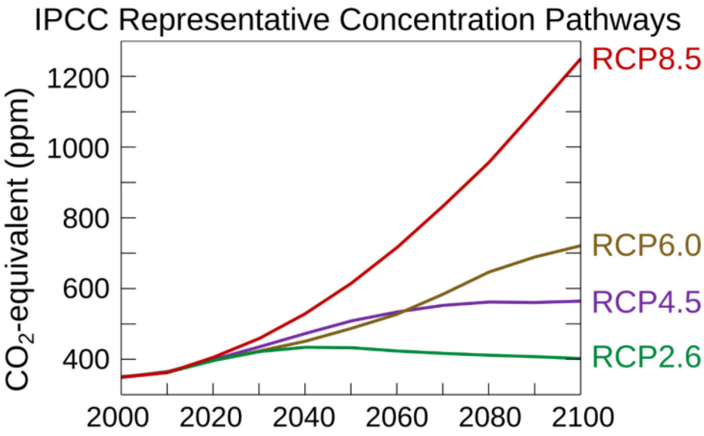


Figure 4. Different Representative Concentration Trajectory Scenarios (Wayne, 2024)

As seen from Figure 4, there are 4 primary RCPs. **RCP2.6**, a scenario showing long-term greenhouse gas emissions aiming to keep the global mean temperature below 2°C. **RCP4.5**, a scenario where emissions reach their highest around 2040 and start to decline, reaching a moderate level of warming. **RCP6.0,** a scenario where emissions reach their highest around 2040 and start to decline, reaching a higher level of warming. **RCP8.5**

shows a high-emission scenario that we are heading towards most likely, where emissions continue to rise, leading to out-of-hand high warming (Wayne, 2024).
RCP8.5 is the higher emission scenario linked to the Arctic amplification, where polar regions warm faster than other areas in the world, implying snow and ice cover, which reduces surface reflectivity and speeds up warming. Precipitation patterns project the same thing, showing that it rains more than it snows, leading to milder winters. Summers in this case are predicted to become hotter, which leads to frequent heatwaves. This will affect Finland's ecosystems, agriculture, and infrastructure, leaving no choice but to adapt to these measures of the evolving climate.

According to Olsson et al. (2015), the changes in atmospheric circulation patterns, aside from the effects of greenhouse gases, have a crucial role in Finland's climate. One is the North Atlantic Oscillation (NAO), which influences the flow of warm or cold air to the region. These circulations are air masses that directly affect the precipitation along with temperature. The shift changes in the circulation patterns are the contributing factors interacting with the global climate that could lead to unexpected short-term anomalies in Finland even amidst long-term warming trends. If the NAO is positive, it brings mild winters and wetter conditions, whereas a negative phase can lead to below-average temperatures and drier, colder winters (Juntunen & Asikainen, 2023).

The findings by Olsson’s team suggest that the trends show the frequency of warm air has interrupted the observed warming trends, which means that aside from greenhouse gases, it causes fluctuations in temperature on shorter time scales. The combination of natural variables in circulation and human-caused warming has resulted in complications of specific weather events attributed to climate change. The long-term trend is evident: Finland is becoming warmer, and the circulation is a contributing factor (Olsson, 2015).

Finland has vast forests, lakes, and snow areas that have a role in local climate agitations. Snow reflects a large portion of solar radiation, and should Finland continue to warm, the snow cover will diminish, leading to a reduced albedo effect and allowing more solar energy to be absorbed by the land surface. The albedo effect refers to the amount of sunlight (solar radiation) reflected by a surface but not absorbed. A higher albedo indicates that a surface reflects more sunlight. This phenomenon accelerates warming, especially in the north. The Finnish government has reported the loss of snow in the Arctic parts of Finland. These parts have higher warming rates than the global average. Declining sea ice has consequences on Finland's climate as well. The Finnish government has pointed out that the northern region is experiencing more rainfall and seasonal shifts, leading to alterations in Finland's hydrological systems. There is an overall increase in moisture in the atmosphere, and as the air warms, it holds more moisture, which leads to intense precipitation events. This implies that there will be changes in agriculture, water management, and flood risks across Finland (Olsson, 2015).

Lieskoski et al. (2024) suggest that although climate change is increasing, Finland is becoming hotter, which could lead to severe droughts affecting Finnish energy systems, due to a potential challenge of reduced water availability for hydropower generation. Severe droughts could decrease water levels of reservoirs, resulting in low water capacities for hydropower and energy supply shortages (Lieskoski et al., 2024).

Since solar energy is expected to increase, it is safe to say that the use of solar panels for renewable energy generation is on the rise. It is plausible that Finland’s government may invest in installing more solar panels to capitalize on the opportunity.

Climate change has influenced Finland's energy production in several ways. The country’s commitment is to combat climate change, which has shifted it towards renewable energy sources. The awareness of environmental issues and securing limits to emissions has sped the adoption of renewable energy technologies. Reliance on fossil fuels has been slowly terminated as Finland's energy production has leaned more toward renewables. This also presents challenges as the significance of energy storage solutions has grown as a contributor to the increase in renewable energy generation. Thus, the impact of Finland's climate on different energy storage solutions needs to be reviewed, especially during harsh winters (Puhakka, 2020).

Puhakka emphasizes that it is better not to increase climate change in Finland as it poses adverse effects on the environment, ecosystem, and human society. Even though it may increase renewable energy production, the negative consequences far outweigh the benefits. Finland’s future possibilities include continuing growth of renewable energy sources, particularly biomass and forest-based energy, and increasing battery energy solutions to balance supply and demand for environmentally friendly energy systems (Puhakka R, 2020).

The situation is black and white. How can we have a sustainable future, and anticipate an increase in renewable production while maintaining a balanced climate for Finland? It can be imagined that Finland doesn’t need to contribute to greenhouse gas emissions, but allows other countries to steadily increase emissions and alter the climate through their national policies. As Finland's climate changes a lot, it is possible to gradually decrease fossil fuel production and increase production in the renewable department. It is now understood that the north will be the first to be affected by global warming. Therefore, at one point, Finland will benefit from the climate change that shifted from the rest of the world to the north. The ethical question is whether the Finnish population prefers warmer winters or fluctuating cold conditions.

According to the Finnish Meteorological Institute, global warming causes warm air currents to pass through the southern parts of Finland, while winter temperatures are rising more than summer temperatures. Cold winters are becoming less common with fewer fluctuations, it will become cloudier, and snow cover is in decline, thus heavier rainfalls (Finnish Meteorological Institute, 2017).

Every indication points towards strong energy production in renewables. Since the Summers are not increasing at the same temperature speeds as Winters. The increased rainfall means more hydro production, warm winds mean higher wind production, and snow cover decline means more chances for solar power production. On top of that, this answers an ethical question: Finnish people would most likely have a better quality of life globally with less cold weather and enjoyable summer vacations. Therefore, I can't entirely agree with Puhakka's context of decreasing climate change in Finland. By the time the floods become a threat to Finland, Finland, along with other countries, will have come up with possible solutions that could be implemented to combat them. Finland does not experience hurricanes or tornadoes to enhance the flood phenomenon, so it is uncertain how many decades it might take until floods pose a risk to Finland.

3.2 Renewable Energy Growth and Battery Storage Solutions in Finland

Figure 5 shows the impact of carbon dioxide emissions on agricultural greenhouse gas emissions. It covers the emissions from land use, forestry, and agriculture, where Finland's climate policy, outlined in the Climate Change Act, targets strengthening carbon sinks. Compared to levels in 1990, emissions are reduced by 60% by 2030 and 80% by 2040, and with this, the final result is to achieve around a 90% reduction by 2050.

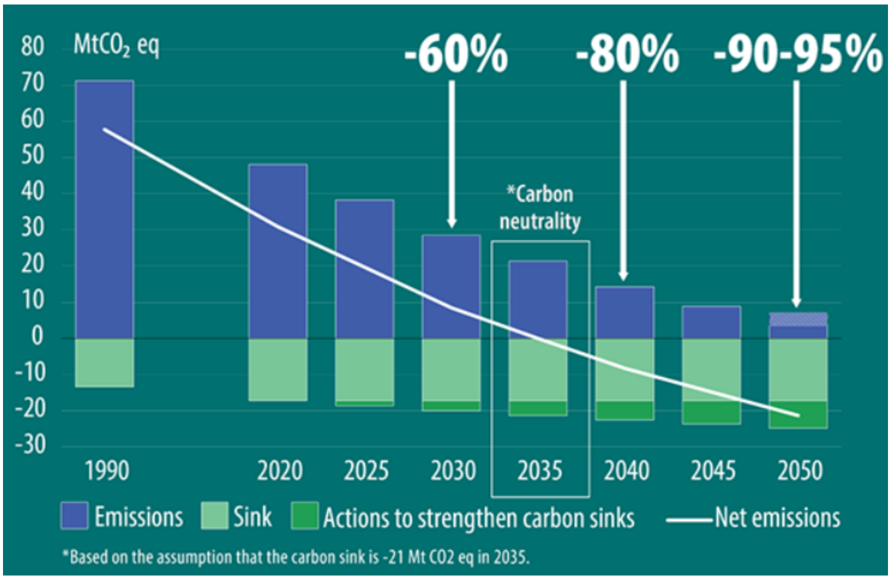


Figure 5. The emission reduction targets in the Climate Change Act (State Treasury Republic of Finland, 2024)

The net sink refers to the balance of carbon emissions and removal in the land use sector. When the land emits and removes carbon from the atmosphere, it is called a carbon sink. When the land sector emits more carbon than it removes, it is called net emissions or ''carbon emissions'' (Ministry of the Environment Finland, 2022).

The State Treasury Republic of Finland addresses several measures and strategies to reduce carbon dioxide emissions and transition towards sustainable and renewable energy sources. Primarily expanding wind, solar, and bioenergy, eliminating coal by 2029, and decreasing oil and gas dependency. It suggests that reducing emissions from transport sectors will have a considerable impact. Finland would promote electric vehicles, improve smart city public transportation, and implement emissions trading in road transport (State Treasury Republic of Finland, 2024; Ministry of the Environment Finland, 2022).

Additionally, Finland would aim for more effective food production in the agricultural sector, reducing emissions per unit produced. Managing the wetlands would reduce environmental burdens. The land removes carbon from the atmosphere through a process known as carbon sequestration. These are well-known as photosynthesis, soil sequestration, reforestation and afforestation, and wetlands and peatlands. In photosynthesis, the plants and trees absorb CO_2 from the atmosphere. In the soil sequestration, when the vegetation dies, its organic matter decomposes, becoming soil and storing carbon in the ground. Some of the carbon in the organic matter is released as CO_2 through respiration, and some of it is stored within it and remains in the soil, forming a stable form of carbon that stays in the ground for decades (Ministry of the Environment Finland, 2022).

Afforestation is about planting new forests to work as photosynthesis, or better referred to as carbon storage. Wetlands and peatlands store large amounts of carbon as peat, which is accumulated from dead plants that decompose in wet conditions. Therefore, strengthening the carbon sinks and pools plays a crucial role in regulating the concentration of CO_2 in the atmosphere to reach carbon neutrality by 2035 (Ministry of the Environment Finland, 2022).

As Finland projects plans to move towards more renewables in the coming years, it needs to be able to store all the excess energy produced. The solution for this is Battery energy storage systems (BESS) to stabilize and balance electricity grids, particularly in markets identified by volatility in the increasing reliance on renewable energy sources. Unfortunately, renewable energy sources like solar and wind occur irregularly, generating electricity in certain conditions. This means it creates imbalances in the electricity supply and demand, leading to blackouts if we rely solely on renewables as an energy source (Olajiga et al. 2024).

Fortunately, BESS can combat these issues by storing the energy produced during high seasons and then releasing it when the generation is low at other times, ensuring that fluctuations are kept out and power is supplied consistently. On top of that, if there are equipment outages, BESS can rapidly push power into the grid, stabilizing the frequency levels. Finland is adding more BESS benefits of load management to flatten the demand curve during off-peak periods and peak periods. This reduces the additional generation capacity, which can lead to lower costs and emissions (Olajiga et al. 2024).

This is a way forward in steadily adapting to the increased climate events in Finland for energy production. For example, during the winter, when winds are intense, wind power still does not meet individual needs. With stronger winds developing over time, alongside improvements in energy storage, wind power will become more reliable. When the climate is harsher, it can be assumed that, with enough battery storage and wind-powered energy produced, it will be enough to lessen the energy-saving burden across all seasons.

Battery storage systems can be costly in Finland and many other countries. Therefore, buying it from abroad won't be a cheaper solution. The expenses of battery storage depend on the technology, the system's capacity, and installation. The demand for energy storage solutions has been increasing in Finland for the past years as the growth of renewable energy sources like wind and solar power is being invested in. This was most likely one of the reasons that led to demand affecting the prices. The government has encouraged the transition to renewable energy production, improving and developing the infrastructure and technology so that the fees towards battery energy storage may have tax breaks and reduced charges to pursue the 2035 objective. The battery storage in Finland is more affordable than it would have been without government incentives. The investment in battery storage might be vital, and the long-term benefits, like energy independence and savings on electricity bills, will be worth considering for many households and businesses. The prices and technologies are constantly changing within the energy market, making it volatile (Olajiga et al. 2024).

Deploying energy storage solutions for grid efficiency faces challenges. These include the high upfront cost of buying and installing, technical barriers to battery cycle life, degradation, and safety issues. Some storage technologies also need specific geographic conditions. Energy storage systems need standardized protocols and interoperability for grid integration. Solutions for these challenges rely on actions of policymakers and regulators, in collaboration with the industry stakeholders, to develop standards for flawless operation and compatibility between different energy storage technologies (Olajiga et al. 2024).

Olajiga et al. (2024) imply that the trends and opportunities are leaning towards advancements in improved chemistries and control systems, which contribute to the scalability of BESS. There is a potential for large-scale energy storage solutions. Policymakers should focus on developing financial reforms for new technologies that accelerate the adoption of energy storage solutions. BESS prices are decreasing as the technology advances. Therefore, encouraging investments in energy storage projects without delays in approvals is crucial with clear regulations. Funding for research drives innovation, reduces costs, supports the development of new materials, and enhances battery control systems (Olajiga et al. 2024).

Once the proper standards are facilitated, widespread adoption of energy storage solutions is to be seen. Ultimately, new technologies do not necessarily mean battery storage will become expensive. As research and development efforts progress, it is anticipated that innovation will lead to a reduction in costs (Olajiga et al. 2024).

This process might still take a while, and it is implausible to expect innovations to appear out of nowhere. The previous versions of BESS are becoming increasingly affordable, and there is a growing demand for new technologies. Finland can invest in the old battery storage in the meantime. This will boost production and yield a high return on investment to explore new technologies to replace old battery storage systems.

Figure 6 shows a projection of where the demand for battery energy storage systems is going as the prices are becoming cheaper globally. It shows the size, battery type, and years of forecast within the market.

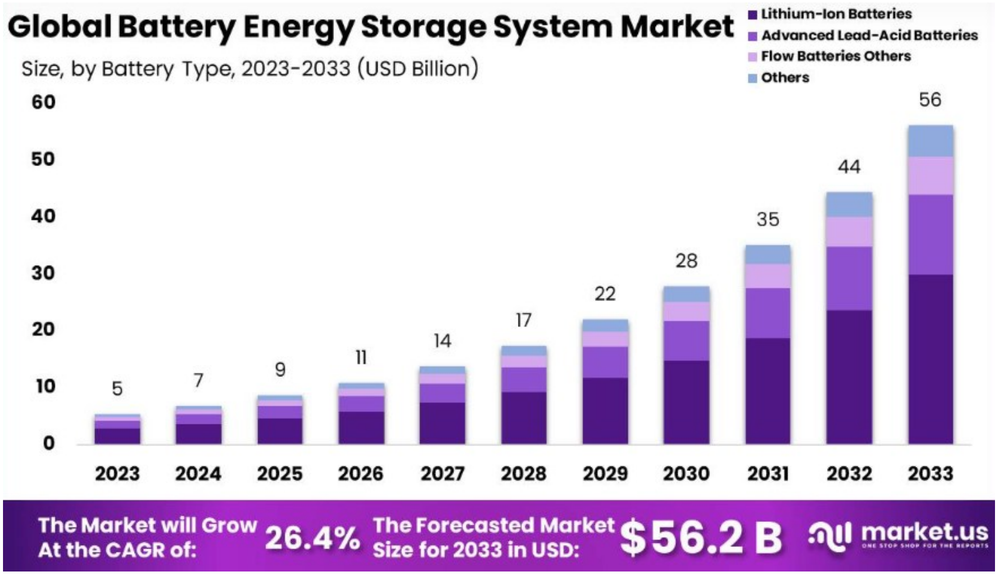


Figure 6. Global battery energy storage system market (Market.us, 2024)

The increased demand for renewable energy sources is the key influence in pushing the BESS market. This includes the growing investments in smart grid projects and the need for energy storage in data and telecom centers. Globally, the adoption of electric vehicles is growing, for more efficient and sustainable energy, further contributing to the increasing BESS market. The government has a significant role in supporting the deployment of the market. In the coming years, the market value is rising sharply from around 5 billion USD in 2023 to 56 billion USD in 2033. The compound annual growth rate is around 26%, attributed to the growth and demand of renewable energy, advanced battery technologies, and the adoption of electric vehicles. The key players in the market of battery energy storage systems are EnerSys, BYD Company Limited, EVE Energy, Siemens AG, LG Energy Solutions, Kokam, Narada Asia Pacific, ABB Ltd., Tesla, Fluence Energy, General Electric, TotalEnergies, Tata Power Company Limited, Samsung SDI, Nissan Motor, VRB Energy, and Black & Veatch Holding Company (Market.us, 2024)

The high cost of Battery storage systems explains why Finland still imports energy from other countries during periods of insufficiency. Still, the cost of battery storage systems has been decreasing in recent years, making them more accessible for various applications. The main applications for BESS by Market.us (2024), is for storing energy for residential use, supporting commercial services, and utility energy solutions with the highest market dominance of 51%, emphasizing that lithium-ion batteries make up 72% of the battery market with an on-grid of 74% shares, popular energy capacity being 100MWh - 500MWh (Market.us, 2024).

Integrating renewable energies like solar and wind power into the grid puts effort into storing extra energy and releasing it when there is a surplus. Solar and wind energy sources are still unreliable in modern times. According to Market.us (2024), lithium-ion batteries are best used for renewable energy source storage and electric vehicles, as they have high energy capacity and best performance. They offer high energy density, low self-discharge rates with minimum maintenance; however, they come at a high cost. The prices seen in the past decade are decreasing. There is an opportunity in large-scale production since the decline has made BESS more budget-friendly for many uses. Companies now invest in larger, more powerful systems for high-demand periods. The price reduction of lithium-ion batteries has driven the growth of BESS (Market.us, 2024).

Challenges arising in Finland's deployment of battery energy storage are found in remote areas. There is a limited grid power source installation, which would need solar panels. Harsh weather conditions such as extreme temperatures, heavy rainfall, and high humidity in isolated areas can affect the lifespan and performance of BESS, which need additional protection and permanence (Market.us, 2024)

Figure 7 below shows historical prices that reflect data from 2013 to 2023, with data points from buses, electric vehicles, and stationary storage. The picture on the right shows the trend of renewable energy sources and battery storage prices over the past years.

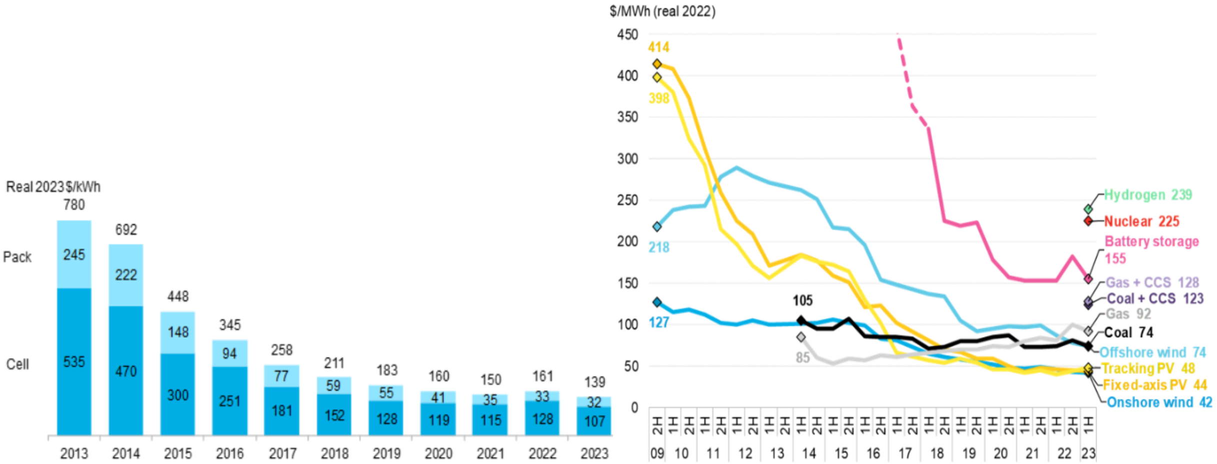


Figure 7. Lithium-ion battery pack and cell prices per kWh and global cost of electricity per MWh (BloombergNEF, 2023)

BloombergNEF (2023) further emphasizes that the decreasing prices of wind power and BESS are contributed by materials becoming cheaper than offsetting debt. Investors are becoming more confident about new wind energy projects, while the equipment costs for clean energy technologies are falling. Solar prices have decreased due to declining polysilicon prices, and BESS equipment costs have dropped due to lithium carbonate prices. According to BloombergNEF, foreign countries have reduced shipping prices for solar panels, wind turbine equipment, and batteries due to recent policy decisions in Asia to alleviate pressure on logistics and manufacturers and keep the supply chain stable for exports (BloombergNEF, 2023). This is also beneficial for Finland, considering that Finland needs as much Asian- and European-manufactured equipment for building renewable energy infrastructures in the coming years as necessary to meet its zero-emission goal.

Looking at Figure 7, positive trends show that onshore wind costs have stayed unchanged globally, and offshore wind and battery storage have decreased in price, a clear indication of the market variation maturing. The resources will be available locally across different countries, making the financial conditions and labor costs feasible for Finland's renewable infrastructural projects. ‘’The regional shift towards local production aims to mitigate future pricing fluctuations.’’ If Finland takes this opportunity, thanks to the lowered input costs, Finland can have a high return on investment for clean energy projects, making it more appealing for investors, leading to Finland fostering a sustainable economic development of exporting their energy instead of buying it all the time (BloombergNEF, 2023).

Figure 8 shows the demand for electric-based vehicles sold in Finland. It shows the predictions from 2025 to 2029. By 2029, the number of EVs will have doubled since 2024, signifying the need for energy production to match the growing demand. The annual growth is 16% from 2024 to 2029 (Statista Market Insights, 2024).

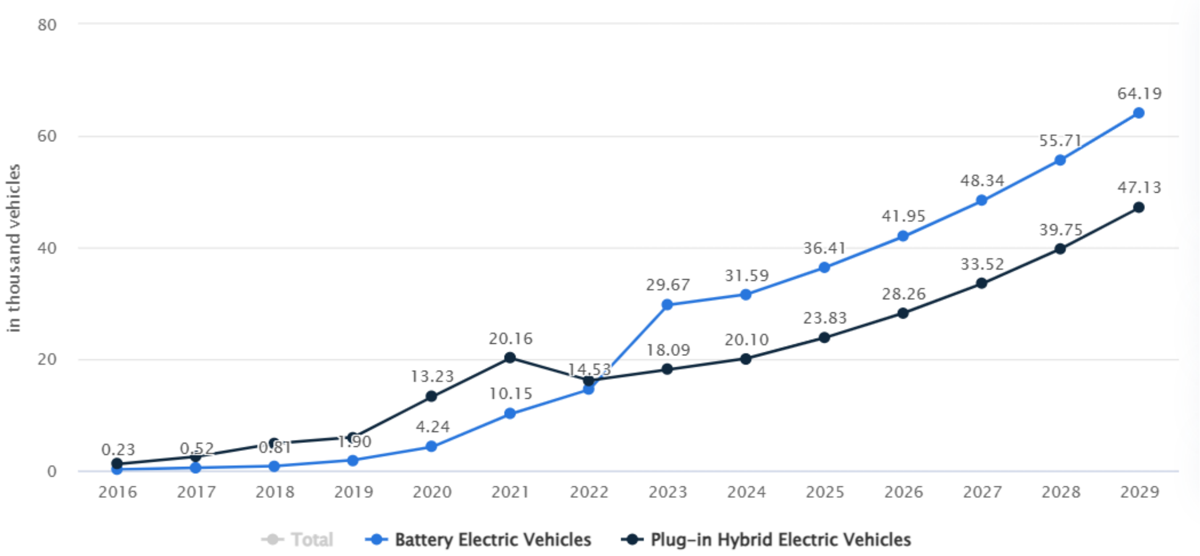


Figure 8. Battery electric and plug-in hybrid vehicle sales in Finland (Statista Market Insights, 2024)

According to BloombergNEF (2023), analysis indicates that the number of battery energy storage systems is growing in Europe, and the demand for them is slowly matching that of electric vehicles. Stationary energy storage systems are increasing by about 50% every year. Manufacturers are manoeuvring through challenges of lower utility rates in plants due to a shortage of demand and revenue. The only problem that is slowing the decision to take a step to boost battery manufacturing in Europe comes down to the complexities of pricing dynamics and higher operational costs compared to Asia. Most manufacturers and products come from Asia, making it cheaper there. The current prices in Europe are higher than in China. China maintains the lowest battery pack prices, while the US and Europe still have market immaturity and economic factors. The investments in R&D facilitation and manufacturing technology could further enhance energy storage solutions, especially in lithium iron phosphate and next-generation innovations to drive down prices and enhance energy storage capabilities over the long term (BloombergNEF, 2023).

The figure below shows the daily and monthly ratio of actual electrical energy output from Solar PV and Wind for a year. The chart shows the estimates based on production.

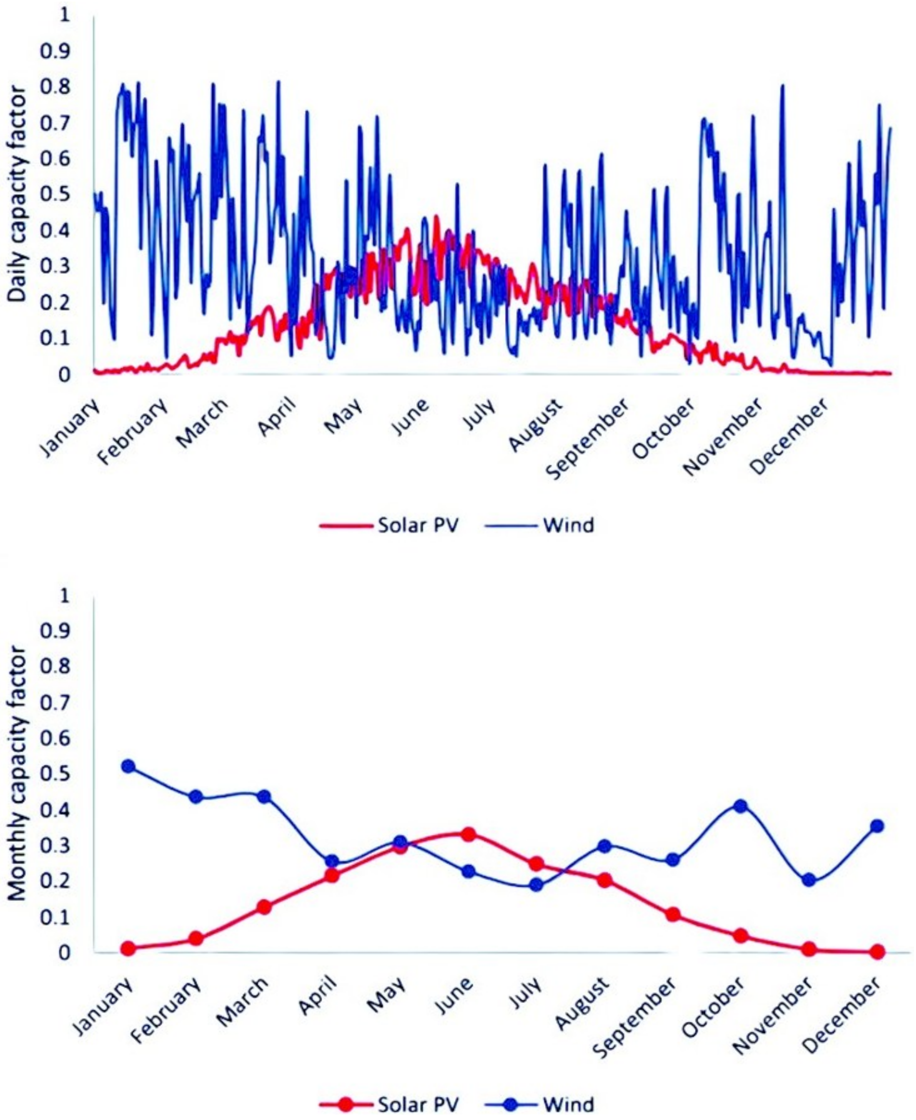


Figure 9. Daily and monthly wind and PV generation in Finland 2023 (Fingrid, 2024)

Figure 9 raises questions about how Finland would cope with future increases in fluctuation: Wind and solar energy can complement each other as they are two sides of the same coin. The wind production capacity factor is about 2.5 times more than solar production, as solar has its highest output during the daytime and less at night. Once Solar PV production increases in the coming years, power-to-hydrogen systems that store excess energy during solar production peaks can convert it into hydrogen. This method provides a solution for long-term seasonal storage due to the nature of seasonal solar production, allowing for later energy use during its lowest periods, even for residential purposes (Huber et al., 2014).

A finding by Zakeri et al. (2015) projects that Finland's wind power systems in 2026 could manage around 200% or 164000 GWh of the country's 2022 electricity demand of 80000 GWh without significant infrastructure upgrades (Zakeri et al., 2015). This indicates that government initiatives to upgrade the wind turbines could increase the estimated numbers.

The study by Kuleshov et al. (2019) emphasizes that solar panels would cover most of the residential energy consumption during spring, summer, and autumn. Wind turbines would cover the remaining energy needs of the other seasons, as shown in Figure 9. Considerable photovoltaic (PV) production is sold to the local grids for a reward. The electricity prices from the grids are three times higher than what is offered for selling electricity back. Therefore, residents who install PVs on their house rooftops for potential self-consumption benefit most when they maximize the utilization of renewable energy to meet their household energy needs. This also leads to favorable conditions for battery storage investments in Finland. The study forecasts imply that, because lithium storage costs are reduced, both BESS and PVs will be profitable each year from 2018 to 2035 (Kuleshov et al., 2019; Luth et al., 2018).

3.3 Solar, Wind, and Hydro projects in Finland

The current energy storage projects Finland is developing include solar parks, wind power plants, battery hybrid solutions, pumped storage hydropower plants, battery energy storage systems, second-life batteries, seasonal hydrogen storage, district cooling energy storage, and rock cavern heat storage (Lieskoski et al., 2024; Ilmatar, 2022). Integrating energy storage solutions with solar and wind power installations addresses the intermittency of solar energy, minimizing traditional fossil fuel-based power generation. Ongoing wind energy projects in Finland under construction include wind farms in various locations such as Lakiakangas, Teuva, Isojoki, Alajärvi, Kyyjärvi, and Salo with improved technology and taller towers. After 2019, offshore wind projects have primarily been developed for commercial use, making them the cheapest electricity source in Finland. Additionally, the feed-in tariff subsidies from 2011 have boosted wind farm projects (Vakkilainen et al., 2017; LevelTen Energy, 2020; Finnish Wind Power Association, 2024).

Solar energy developments planned for 2025 are located in Helen Lohja and at Raahen Solar Park. The Energy Hybrid Park will integrate wind and solar energy planned for Ilmatar with the Hämeenkylä Battery Energy Storage facility in Salo. In addition to this, virtual power plants represent a new concept in the energy industry, a project of multiple decentralized energy sources integrated into a unified network. They function as a single coordinated power plant consisting of solar panels, wind turbines, energy storage systems, and demand response systems controlled centrally, offering peak shaving. Plans are underway to implement this at Sinecrychoff Brewery (Lieskoski et al., 2024).

As of 2024, the current projects under construction are wind power projects expected to be completed by the end of 2024. Decentralized integration generated from previously mentioned renewable sources, as well as natural gas, is used locally, for residential, commercial, and industrial use. Decentralized systems are used for independent operation, and if one source fails, the other continues to operate, enhancing grid resilience. Decentralized energy systems are innovative options for communities, as they have lower environmental impacts. By comparison, centralized energy systems operate with large facilities, with longer lead times for development, impacting the environment. They also require more investments and transport energy over long distances to consumers, which is unfavorable. One wind farm, Helen Lakiakangas 3, is located in Kristiinankaupunki and Isojoki, another in Teuva, and an MW storage is in Ikaalinen. Solar and wind power parks contribute to renewable energy, facilitating the reduction of fossil fuels and the development of more energy storage systems. Following 2019, solar power projects were planned to receive subsidies to help industries or businesses keep the price of commodities or services low (Lieskoski et al., 2024).

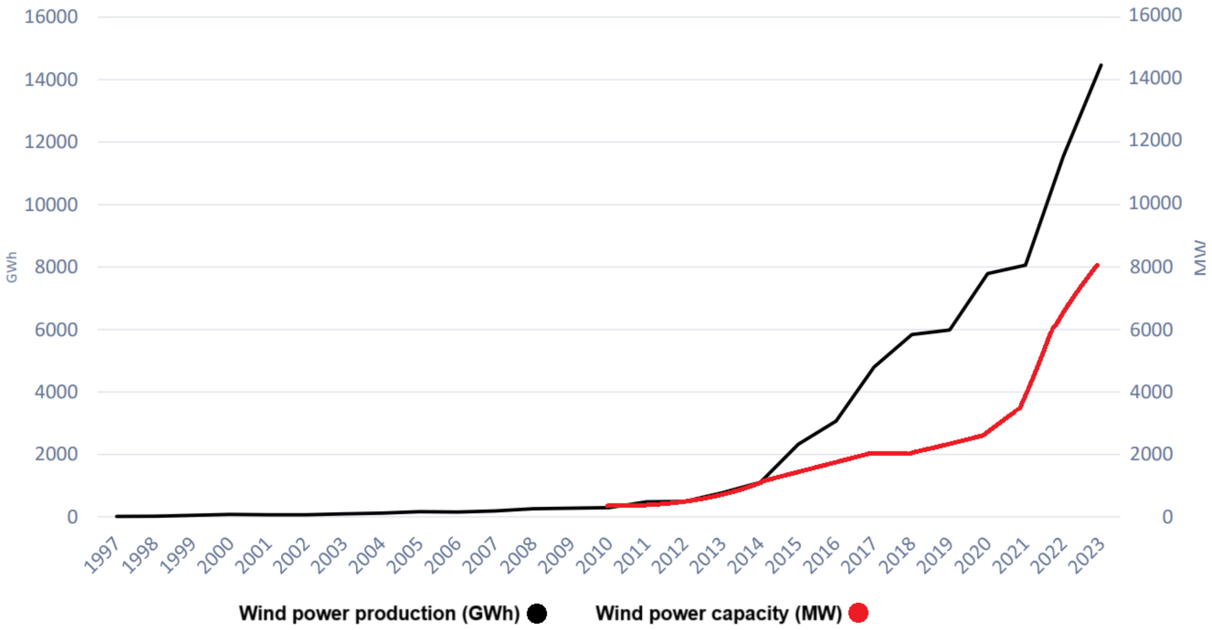


Figure 10. Annual Wind power production and capacity (Finnish Wind Power Association Statistics, 2024)

The data demonstrated in Figure 10 shows that the performance in the early years was not impressive, generating an average of around 16%. Wind power sites in the early years were situated in poor locations, unable to enable wind turbines to generate at maximum capacity. Only after wind turbines were relocated and improved upon, Finland started to see changes in performance of up to 34% of electricity production (Finnish Wind Power Association, 2024).

When hydropower energy storage has surplus electricity, it is used to pump water to higher elevation reservoirs and is released to generate electricity during high demands. Finland has an abundance of biogenic CO_2 and natural reserves like metals, precious metals, and rare metals that contribute to renewable energy resources in Finland's innovative strengths. Finland has high potential as a future clean energy country relevant in hydrogen production, because of the leading technology solutions and workforce in forests, maritime, chemical, and refining industries, giving a competitive advantage (Lieskoski et al., 2024).

Finland is currently the second-highest ranked innovative country in Europe and globally twelfth in research and development. Finland currently accounts for 10% of Europe's clean energy in hydrogen use. The development of hydrogen attracts market conditions to funding and investments through a large influx of direct public support towards building Finland's hydrogen economy, including battery energy storage (Lieskoski et al., 2024).

The energy storage technologies include energy that can be stored electrochemically through pumped hydropower storages, with capacitors in thermal energy storages, and using chemical energy as hydrogen and its derivatives (Lieskoski et al., 2024).

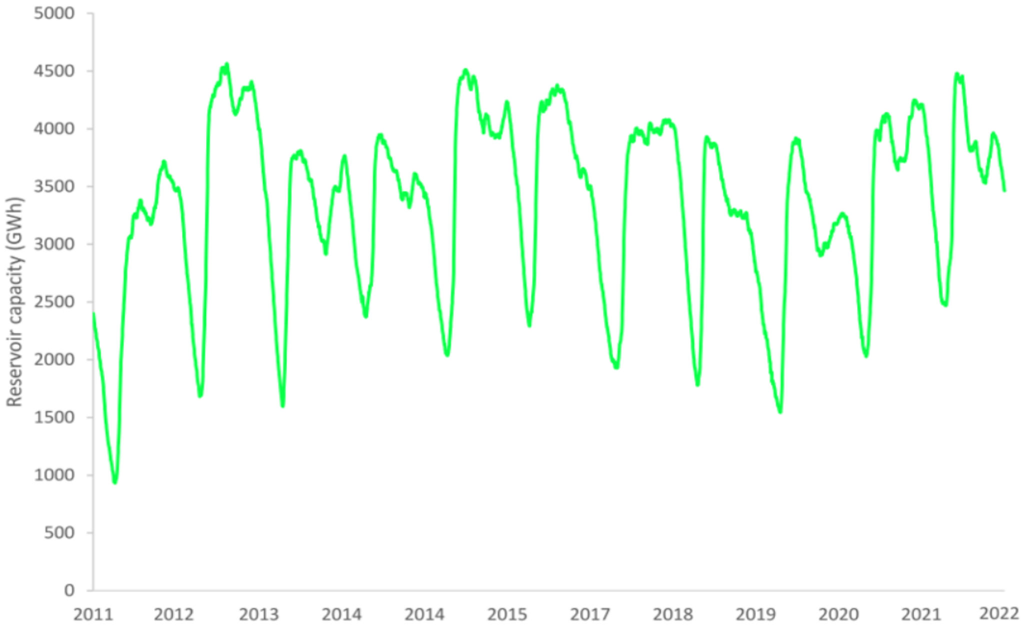


Figure 11. Hydro reservoir capacity (GWh) in Finland from 2011 to 2022 (Finnish Environment Institute (SYKE), 2024)

The pattern in Figure 11 shows that run-of-river plants account for one-third of Finland's hydro plants, which have utility limits and power regulation. This is different from wind and solar energy sources influenced by weather. Water reservoirs are at their highest in May and lowest in April. Due to Autumn rainfall, reservoir levels rise. Fluctuation depends on precipitation levels. These are vital to planning when forming energy generation for flexible use of energy storage systems and demand response (Finnish Wind Power Association, 2024; Finnish Environment Institute (SYKE), 2024).

As one of the largest-scale investments currently in Finland, hydropower plants offer several benefits and advantages in the country's energy landscape. These include ensuring stability in unexpected outages, providing a consistent power supply that can be dispatched to help mitigate the variability of wind and solar power, and bringing economic growth by reducing the need for costly peaking power plants when optimizing existing hydropower infrastructures (Karhinen et al., 2019; Ministry of Economic Affairs and Employment, 2021).

Finland has adequate water availability from rivers to lakes and even artificial reservoirs for filling and maintaining the upper and lower reservoirs. The operation of hydropower energy storage is best integrated into mountain regions of high elevation. Natural elevations or areas above sea level are advantageous, as they create upper and lower reservoirs that can harness gravitational potential energy. Water can be stored at the upper reservoir and then released to flow to a lower reservoir to generate the required electricity (Gimeno et al., 2013; Finnish Environment Institute, 2023).

The construction of dams and tunnels facilitates water flow between reservoirs, which is significant for maintaining water levels. It also minimizes water loss due to evaporation and ensures efficient energy generation. Additionally, coastal areas are a strong producer where tidal currents are harnessed into energy (Gimeno et al., 2013; Finnish Environment Institute, 2023).

Lieskoski et al. (2024), emphasize that it is crucial to select sites where environmental impacts can be integrated into the generation process while minimizing the environmental impact during the energy generation operations. These sites should take seasonal variations into account. It is also crucial to reduce transmission losses by identifying proximity to energy demand centers for efficient delivery to consumers (Lieskoski et al., 2024).

3.4 Finland’s future in hydrogen production

Finland’s National Hydrogen Roadmap focuses on developing a domestic hydrogen value chain, expanding electrolysis capacity, implementing support programs for hydrogen projects, and international collaboration aiming to produce a lot of hydrogen to export to other countries. Finland recognizes the potential for economic growth and a secure energy transition in critical mineral mining and the battery supply chain, leveraging its abundant deposits of cobalt, nickel, lithium, graphite, and other crucial minerals, with Finnish companies expanding production and refining a significant portion of global cobalt output. The hydrogen strategy outlines the path towards a hydrogen economy in Finland (Laurikko et al. 2020).

Hydrogen has substantial global climate benefits and can reduce carbon emissions in sectors such as iron production, replacing C02. Power-to-X (P2X) incarnates the hydrogen economy, which uses renewable electricity and captured low-carbon emissions to produce electric fuels (Laurikko et al., 2020). The figure below shows the projected hydrogen demand in the EU for 2030 and 2050. It suggests the opportunity for Finland to join the hydrogen market in the near future.

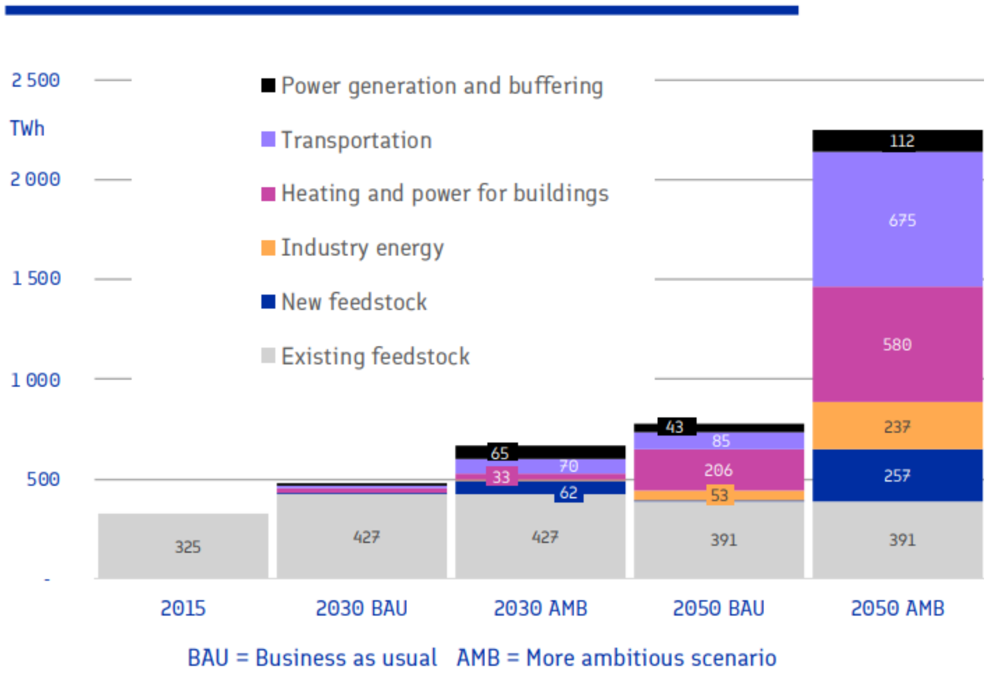


Figure 12. Expected growth of hydrogen use in Europe by 2030 and 2050 (Laurikko et al., 2020)

Hydrogen can be used for existing fuels, logistics, and refueling infrastructures. Additionally, it can be used in modern-day vehicles powered by combustion engines. It is seen as the solution to transition to a fully emission-free country. A key consideration for the use and storage of hydrogen is its transportation through Finland's natural gas pipelines. Hydrogen will be transported by trucks for cost-effectiveness. Finnish manufacturing depends on heavy transports and materials, which opens a pathway to potential hydrogen fuel cells for heavy transport applications, mobile machinery, and marine applications. Finland's archipelago regions are seen as potential test areas for hydrogen due to wind power opportunities and different-sized vessels (Laurikko et al., 2020; Hydrogen Cluster Finland, 2023).

Beyond pipeline storage, lined rock caverns are also necessary storage. Finland aims to increase hydrogen production by increasing the production of low-carbon capture. These are produced by leveraging renewable energy sources, such as wind power and photovoltaics (PV). Upon achieving proper hydrogen production, Finland is expected to replace blast furnaces with electric arc furnaces, which require a significant amount of hydrogen gas (Laurikko et al., 2020; Hydrogen Cluster Finland, 2023).

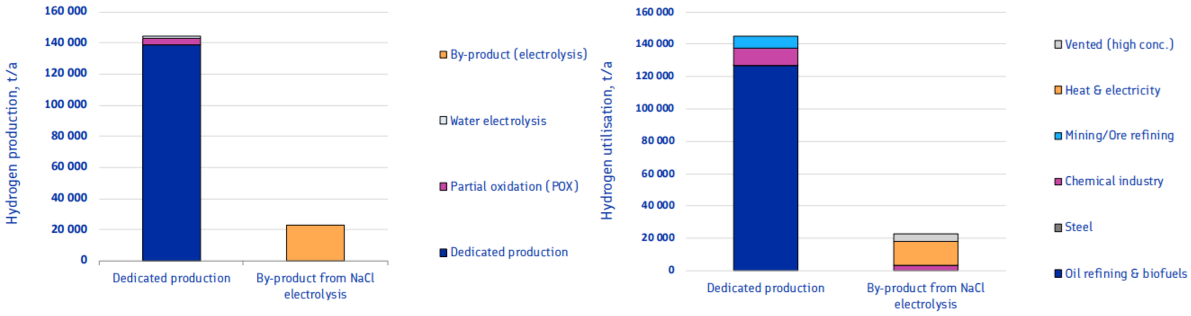


Figure 13. Current hydrogen production in Finland (Laurikko et al., 2020)

Figure 13 represents Finland's options for hydrogen production. Finland produces its hydrogen mostly through steam reforming and oxidation of fossil fuels, with less than 1% comes from water electrolysis. The water electrolysis is generated from sodium chloride and oil refining. Most of the dedicated hydrogen is used for oil refining and biofuel production. The rest is used for the chemical industry, mining, and a small amount for the steel sector. Finland generates steam and district heat from electrolysis, combining it with hydrogen in the atmosphere for future applications (Laurikko et al., 2020; Hydrogen Cluster Finland, 2023).

Regional variations affect the price of hydrogen. Traditional hydrogen production methods are steam reforming, partial oxidation, coal gasification, and electrolysis. Finland has less competition in these regards. It is one of the countries where cheap natural gas is available, making hydrogen production costs low. The decreasing wind and photovoltaic prices in the market contribute to it. This also indicates that low transportation costs help position clean hydrogen as an economically viable solution (Laurikko et al., 2020; Hydrogen Cluster Finland, 2023).

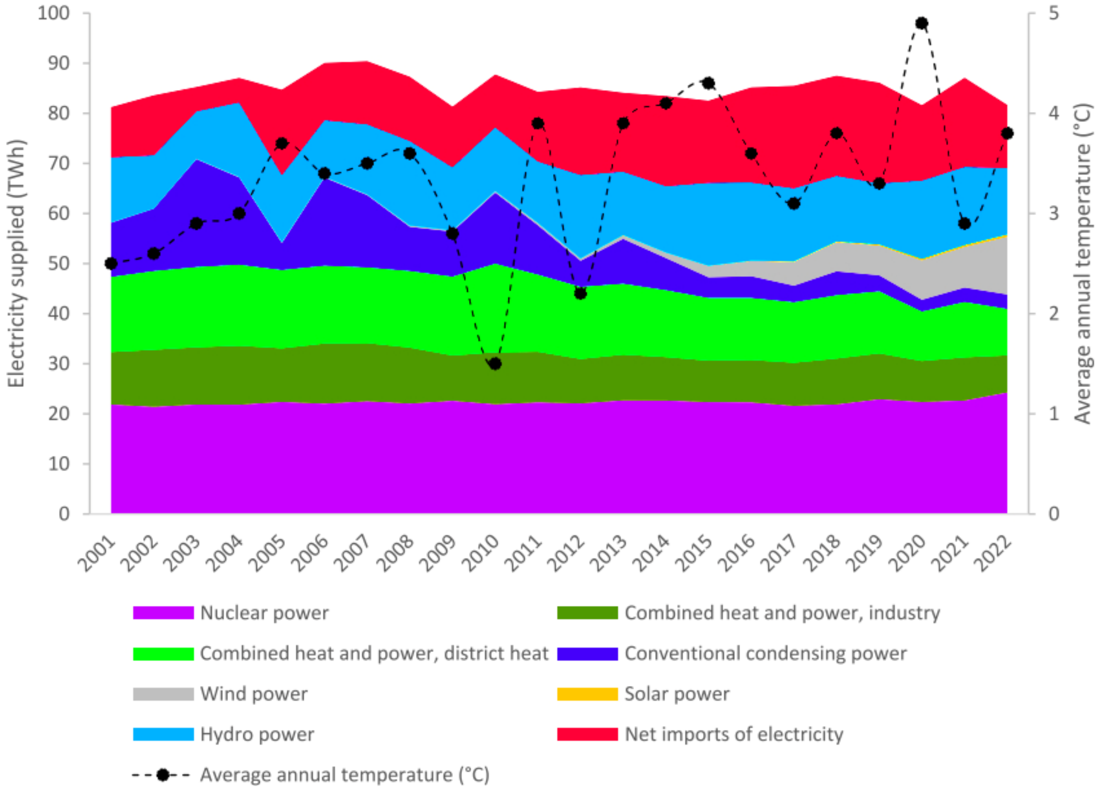


Figure 14. Finland's Annual average temperature and electricity supply from 2001-2022 (IEA, 2024; Statistics Finland, 2024)

Data illustrated in Figure 14 comprises nuclear power at about 30%, thermal power at about 24% or 19.6 TWh, electricity imports at 15.3%, hydropower at about 16%, wind power at about 14%, and solar power at about 1%. Energy consumption has increased since 2022 primarily due to cold climates, low population density, and energy used for long transportation distances (IEA, 2024; Statistics Finland, 2024).

An analysis of energy consumption between 2001 and 2022 reveals considerable fluctuations, mainly influenced by Finland’s harsh winters. The impact of global warming on

Finland is looking positive as winter temperatures continue to increase, leading to reduced energy consumption. The trend shows that electricity consumption has remained stable, although there have been changes in the energy sources (Statistics Finland, 2024; Fingrid, 2022).

Finland had to rely on nuclear and thermal power to produce energy, as the country could not rely on renewable energy as much as in the past. The usage of thermal energy has decreased substantially in the past 20 years. Conventional condensing power generation (power plants, HVAC systems, heat exchangers) has also plummeted within this time frame (Statistics Finland, 2024; Fingrid, 2022).
Wind and solar power are expanding, yet they remain minor contributors to the energy mix. Challenges have arisen from the decline of dispatchable power generation and reliance on renewable energy sources, such as the inability to balance supply and demand, thus forcing Finland to import energy from neighboring countries, especially Sweden (Statistics Finland, 2024; Fingrid, 2022).

Pumped hydropower storage captures 96% of the global market in electricity storage (IRENA, 2017). Finland aims to expand domestic clean hydrogen production by leveraging available renewable sources, accelerating the clean industry, and growing hydrogen technologies and services exports. This will support and strengthen the country's economy, helping it become a major player in the hydrogen economy (Hydrogen Cluster Finland, 2023).

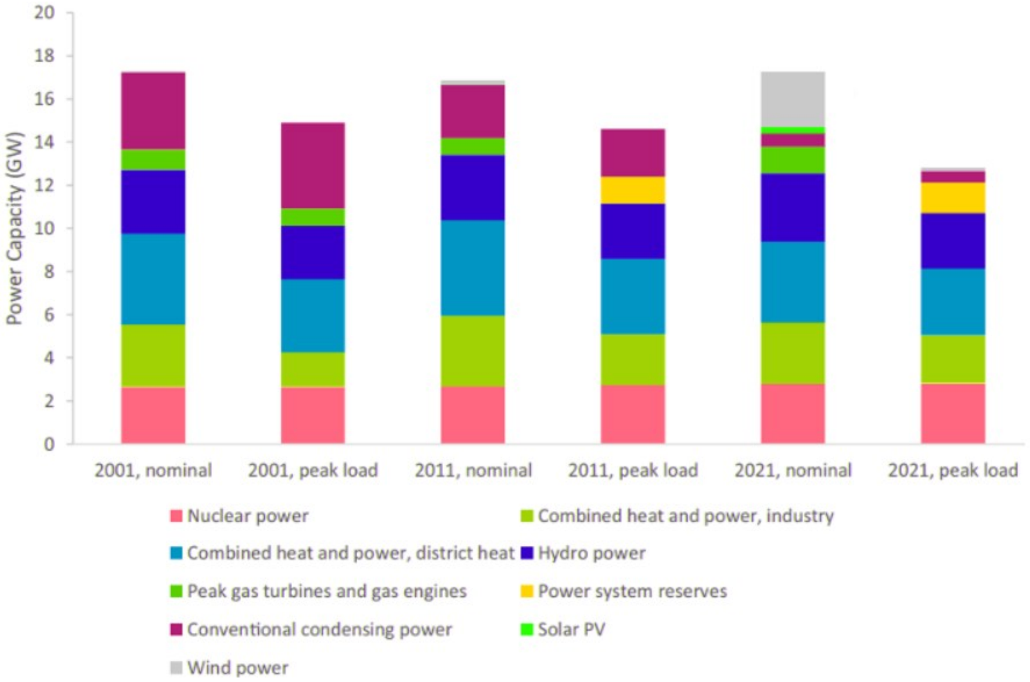


Figure 15. Nominal and peak load electricity generation capacity in Finland for 2001, 2011, and 2021 (Statistics Finland, 2023)

Figure 15 illustrates Finland’s decrease in conventional condensing power and peak load capacity. Peak load is the maximum power generated in an hour, specifically on a cold winter day. During peak load, gas turbines and gas engines generated from hydropower serve as reserves, which account for 90% of the managing reserves. During the 2021 peak load, wind power accumulates only a minor percentage of energy compared to traditional sources during high demands. Since 2021, the trend shows that Finland is relying less and less on electricity imports through interconnections with Sweden, Estonia, and Norway, raising confidence in energy supply security in generating capacity during peak demand periods (Ministry of Economic Affairs and Employment Energy, 2024; Fingrid, 2024).

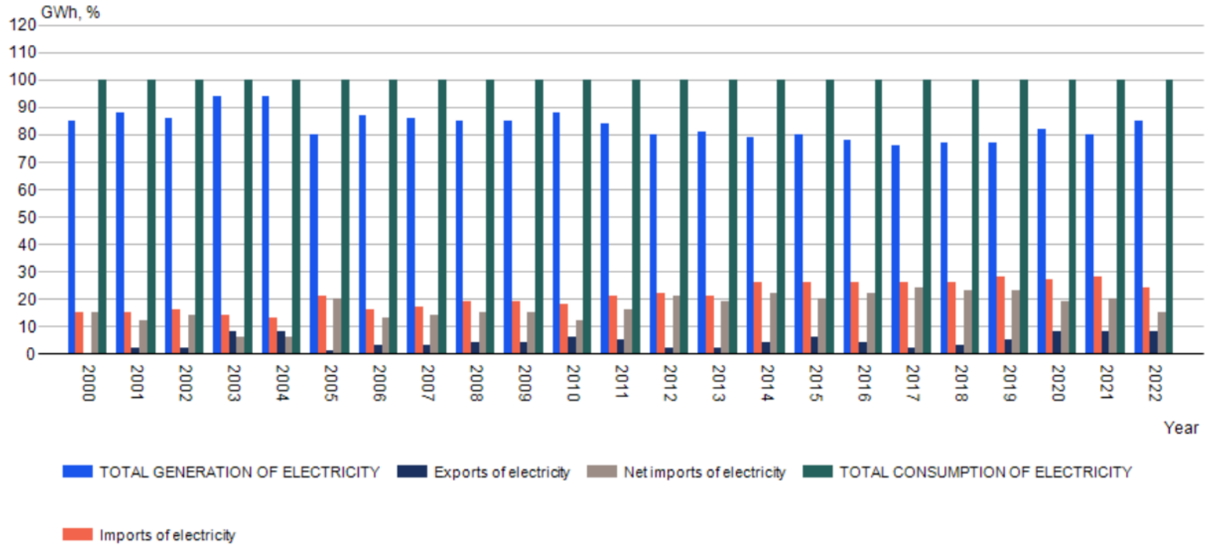


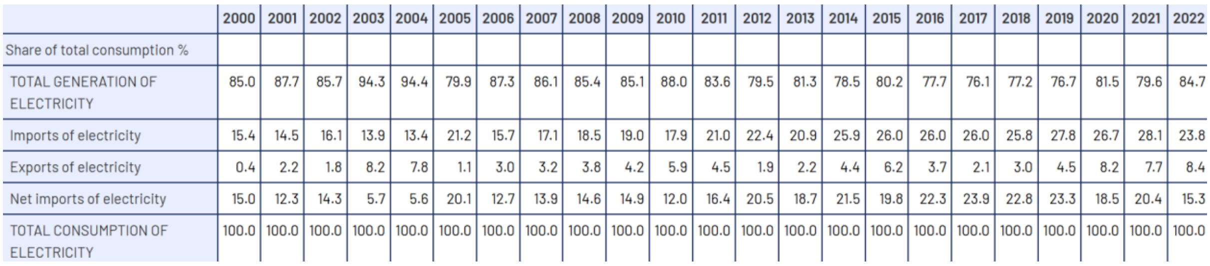
Figure 16. Production of electricity by production/supply and year. Share of total consumption % from 2000 – 2022 (Statistics Finland, 2024)

As seen in Figure 16 and Table 1, Finland is underperforming in electricity production compared to imports from foreign countries. For Finland to become energy-independent, it must produce enough energy to match its exports. Finland must increase its electricity production by 1.5 times to match the net electricity imports.

Required increase in production = (total consumption - current production) + exports

Current production refers to the amount of energy currently being produced. Total consumption indicates the overall energy demand. The ‘required increase in production’ is the percentage by which current production is insufficient to meet the total consumption, which includes the lost electricity on exports.

Table 1. Production of electricity by production/supply and year. Share of total consumption % from 2000 to 2022 (Statistics Finland, 2024)



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Share of total consumption %																							
TOTAL GENERATION OF ELECTRICITY	85.0	87.7	85.7	94.3	94.4	79.9	87.3	86.1	85.4	85.1	88.0	83.6	79.5	81.3	78.5	80.2	77.7	76.1	77.2	76.7	81.5	79.6	84.7
Imports of electricity	15.4	14.5	16.1	13.9	13.4	21.2	15.7	17.1	18.5	19.0	17.9	21.0	22.4	20.9	25.9	26.0	26.0	26.0	25.8	27.8	26.7	28.1	23.8
Exports of electricity	0.4	2.2	1.8	8.2	7.8	1.1	3.0	3.2	3.8	4.2	5.9	4.5	1.9	2.2	4.4	6.2	3.7	2.1	3.0	4.5	8.2	7.7	8.4
Net imports of electricity	15.0	12.3	14.3	5.7	5.6	20.1	12.7	13.9	14.6	14.9	12.0	16.4	20.5	18.7	21.5	19.8	22.3	23.9	22.8	23.3	18.5	20.4	15.3
TOTAL CONSUMPTION OF ELECTRICITY	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Currently, Finland is still consuming more electricity than it produces annually. Looking at 2022’s 84.7% of total electricity generation, Finland must provide the remaining 15.3% domestically to cover its consumption without imports. Additionally, if Finland wants to match the 2022 year's imports for annual revenue, Finland should produce approximately 24% in total and then continue to increase production each year for economic growth. That is only if the country still uses nuclear power as a source of energy. Reaching the goal of producing energy solely from renewable sources will be a different story.

The figure below shows two charts: the left illustrates the origin and quantity of Finnish electricity sources from 2017 to 2024, while the right shows the total annual carbon accumulation.

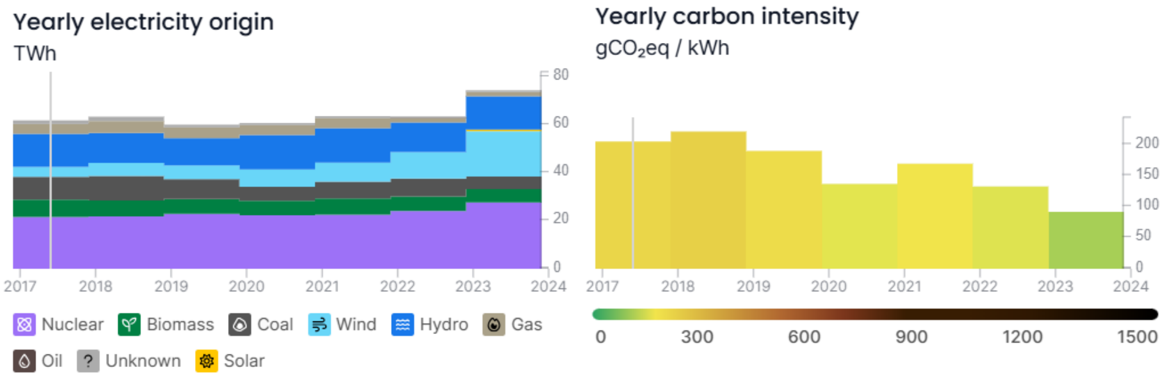


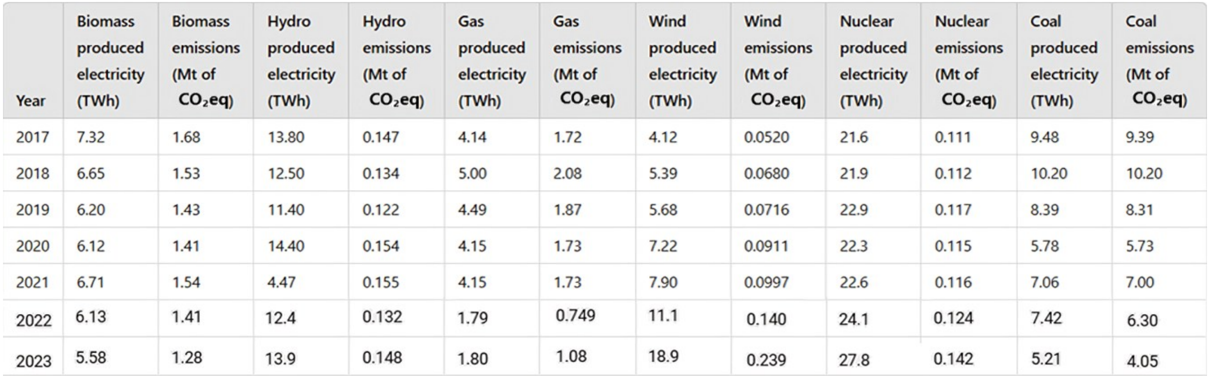
Figure 17. Energy source origin and total carbon intensity from 2017 to 2023 in Finland (Electricity maps, 2024)

Table 2 shows the values and corresponds to Figure 17, which illustrates Finland’s energy source production and carbon emissions from 2017 to 2023. It captures the energy production in TWh and emissions in Mt of CO_2eq for the energy sources. This table provides a view of renewable and non-renewable energy sources and emissions over the years. Solar energy is excluded, for it only has data for 2023 with 0.719 TWh of electricity production and 0.0324 Mt of CO_2eq (Electricity maps, 2024).

The trends of renewable energy sources (Biomass, Hydro, and Wind) increased from 25.24 TWh in 2017 to 38.38 TWh in 2023; emissions decreased slightly from 1.879 to 1.667 Mt CO_2eq. Non-renewables (Gas, Nuclear, and Coal) increased from 35.22 TWh in 2017 to 34.81 TWh in 2023; emissions had a sharper reduction, dropping from 11.221 to 5.272 Mt CO_2eq. The overall change from 2017 to 2023 is the total energy produced by 12.73 TWh (or 12.73 TWh · 3600 = 45828 TJ), while total emissions have reduced significantly by 6.161 Mt CO_2eq.

Finland is steadily reducing non-renewables, which accounts for the decline in emissions. Finland's trajectory in achieving the carbon-zero goal appears promising; the increase in renewable energy production, alongside the reduction of its total emissions, reflects sustainability and innovation, suggesting Finland is on the right path. Non-renewable sectors are seeing a decline in efforts to rely on fossil fuels. This momentum could face possible challenges if the transition is not equitable and economically viable, if strategies investing in the energy storage solution and smart grid technologies are not put in place to manage the fluctuation of renewable energy, which requires government collaboration. Current trends indicate that Finland has the potential to make groundbreaking progress in meeting the carbon neutrality goals.

Table 2. Finland’s energy source production to carbon emissions from 2017 to 2023 (Electricity maps, 2024)



Year	Biomass produced electricity (TWh)	Biomass emissions (Mt of CO_2eq)	Hydro produced electricity (TWh)	Hydro emissions (Mt of CO_2eq)	Gas produced electricity (TWh)	Gas emissions (Mt of CO_2eq)	Wind produced electricity (TWh)	Wind emissions (Mt of CO_2eq)	Nuclear produced electricity (TWh)	Nuclear emissions (Mt of CO_2eq)	Coal produced electricity (TWh)	Coal emissions (Mt of CO_2eq)
2017	7.32	1.68	13.80	0.147	4.14	1.72	4.12	0.0520	21.6	0.111	9.48	9.39
2018	6.65	1.53	12.50	0.134	5.00	2.08	5.39	0.0680	21.9	0.112	10.20	10.20
2019	6.20	1.43	11.40	0.122	4.49	1.87	5.68	0.0716	22.9	0.117	8.39	8.31
2020	6.12	1.41	14.40	0.154	4.15	1.73	7.22	0.0911	22.3	0.115	5.78	5.73
2021	6.71	1.54	4.47	0.155	4.15	1.73	7.90	0.0997	22.6	0.116	7.06	7.00
2022	6.13	1.41	12.4	0.132	1.79	0.749	11.1	0.140	24.1	0.124	7.42	6.30
2023	5.58	1.28	13.9	0.148	1.80	1.08	18.9	0.239	27.8	0.142	5.21	4.05

Below are the graph illustrations of Table 2 values (Finland’s energy source production to carbon emissions from 2017 to 2023) for a visual understanding. it highlights the dominance in Finland’s electricity generation, emphasizing the lower emissions associated with renewables and non-renewables with the higher emissions linked to fossil fuels.

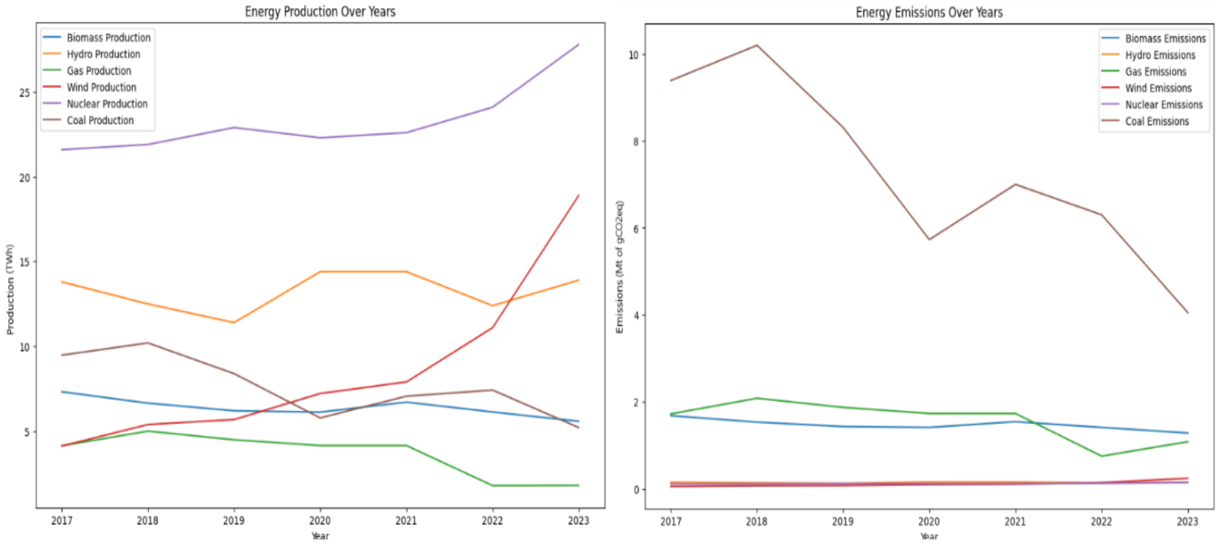


Figure 18. Finland’s energy source production to carbon emissions from 2017 to 2023 (Electricity maps, 2024)

The production chart illustrated in Figure 18 on the left shows the various energy sources used in Finland's electricity generation, with nuclear power as the most important source, followed by hydro, biomass, and wind in that order. Gas and coal have contributed more variability to the energy mix. Most of Finland’s energy is generated from nuclear power, the lowest emitter of greenhouse gases. The emissions chart on the right shows the impact of these energy sources, with fossil fuels—coal and gas—producing the most emissions compared to renewables and nuclear power. Biomass is renewable but also associated with emissions, although they are lower than those of fossil fuels. Hydro and wind have the least emissions, making them the cleanest option for energy as renewable energy sources.

A study in the U.S. by the University of California states that renewable energy sources have increased within just one year by 21% from 2022 to 2023, which should correlate with the climate change increase. The U.S. faces harsher events than Finland's already cold climates, which would negatively affect renewable energy infrastructures, reducing production (Cho, 2024). This is not the case in a cold country like Finland. The article foreshadows potential challenges to face in the far future for countries like Finland if not handled with proper mitigation strategies. Naturally, for renewables to see an increase in production, higher global warming is required in Nordic countries by changing the carbon cycle relatively. Therefore, Finland should consider warming the country by relying on emission-based energy sources to enhance this warming effect for as long as it is safe to rely on renewable energy sources in the long run for the best possible output (International Energy Agency, 2021). Burning fossil fuels primarily causes carbon dioxide ($C0_2$) and nitrous oxide (N_2O) into the atmosphere, raising temperatures and intensifying greenhouse effects (University of California, Berkeley, 2024).

According to a study by the Confederation of Finnish Industries, energy storage projects in Finland create new job opportunities, stimulate innovation in the energy sector, and contribute to further growth in the renewable energy industry. This attracts potential investors toward 100% renewable energy, enabling the largest Finnish economic bloom and acting as a pivotal foundation for other industrial investments (Wärtsilä 2024; Gaia 2024).

3.5 Finnish government incentives

The financial support Finland has for research and development funding projects for new energy technology comes from European Union Funding Programs for new energy technology, government tax reduction, Energy Aid programs from Business Finland, and partnerships with public institutions and private companies (European Parliament, 2019; Business Finland, 2023).

Currently, the challenge for Finland is in the reserve market, which affects profitability because it is not big enough. Battery projects to increase battery storage capacity will help adjust Finland’s fluctuating power supply. Even if there is price volatility in Finland's energy market, BESS is still profitable, giving the opportunity compared to Norway and Sweden. Fingrid’s goal is to increase its reserve market capacity substantially by 2030. This is a clear sign that the next logical step should be to develop services of multiple revenue streams in the storage market, combining storage with wind and solar energy with supportive services to generate income. It is shifting towards the commercial construction viability of BESS without the help of investments, keeping the competition in the energy sector. They generate revenue from grid services, reserve markets, renewable energy integration, demand response programs, peak shaving services for grid operators and market participants, capacity markets auctions, and electricity trading. All of this is driven by the decline of costs for BESS, market demand, and regulatory support given (Bashir et al., 2019; Zakeri et al., 2014; Ramos et al., 2021).

The legislative amendments aim to curb electricity distribution prices in Finland by weatherproofing their electricity networks and investing in underground cables aside from aerial cables to reduce weather-related disruptions. According to Lieskoski et al. (2024), aside from BESS integration, Finland's strategy is to maintain reserves for generation capacity, by supplying only at times when energy is not enough as well as interconnecting with cross-border countries to import and export electricity to balance the supply and demand. Regulatory authorities and system operators, such as TSO and DSO, can reduce this problem effectively by making demand forecast projections to meet the country's needs (Lieskoski et al., 2024).

The key changes since the beginning of 2019 include the government program’s energy taxation plan, which promoted climate action, the increase of coal taxation, and the reduction of natural gas taxation. This encouraged the transition of energy plants from coal to cleaner-burning natural gas for less pollution. Natural gas is also a key component in the fertilizers most farmers use. Bringing down energy costs also makes it more affordable for farmers to produce, reducing the net import of goods (Ministry of Finance, 2018; 2021).

The tax for combined heat and power (CHP) production that generates electricity and thermal energy from the same energy sources, such as natural gas, biomass, or waste heat used in gas or steam turbines, has been halved. Additionally, double taxation on electricity used to charge batteries has been eliminated. This was beneficial for electric car batteries. An employer would not be taxed for charging their EVs at the workplace, as it has become streamlined. heating fuels have been made fairer for everyone by being adjusted to match just as tax fuels used for transportation like gasoline or diesel for cars so that there won't be revenue losses for the government, in consideration of the total emissions produced over the entire life cycle of the fuels (Ministry of Finance, 2018; 2021).

3.6 Finland’s economic state

Finland's net borrowing was 14.2 billion euros in 2023 from 2022’s 19.3 billion euros. Net borrowing refers to the amount of money the government needs to borrow, increasing the repayment debt of financial assets. The Finnish government's gross borrowing requirement in 2023 was 42.3 billion euros (from 34.31 billion euros in 2022), indicating the total amount needed for budget deficits, financing public services, investments, and debts. The 14.2 billion euros is the actual amount after any repayments, a reflection of the actual increase in debt. In 2022, over 10 billion euros were loaned to energy companies to cover electricity margin calls and losses, as the electricity market value dropped below a certain level, usually affected by fluctuating energy prices. The loans were given to maintain the position in the market to supply the demand (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022).

The annual growth for gross borrowing extending to 2027 is expected to remain around 40 – 45 billion, which is 5 billion higher than the estimation from 2022, indicating the borrowing requirements for Finland in the coming years for financial planning.

The investor demand for the Finnish government remains strong as the bonds remain solid. Bonds are loans from investors to the government, leading to periodic interest payments and the return of value when the bond matures. They believe that Finland can meet debt obligations (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022).

The net borrowing from 2022 to 2023 has decreased by 5 billion euros. Interest rates are rising, which means that the amount of money circulating in the economy is going down, often leading to increased borrowing costs for energy companies for new projects, technologies, and renewable energy (State Treasury Republic of Finland, 2024).

From an investor’s standpoint, rising interest rates are a gold mine. However, socially speaking, high interest rates affect GDP negatively by increasing debt. That does not necessarily mean that they are adverse. If investors are seeking safe havens in Finnish bonds, this could mean that the government is pushing corporations to invest in domestic energy sources and infrastructure for energy security. When there is an increasing demand for Finnish bonds, the euro value tends to rise, which affects energy prices, especially in international markets (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022)

According to Teppo Koivisto, Director of Finance, the Finnish government believes that despite debt going up, there is a positive outlook on Finland’s financial management in issuing bonds effectively (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022)

Finland's central bank totals about 156.2 billion in debt, accounting for 55.4% of its GDP in 2023. Instead of borrowing from foreign banks, it takes loans from investors in the eurozone who want to invest in the Finnish market and repays them with the issuance of new bonds and taxes. This could change in the coming years, considering if Finland manages to become energy independent and be one of the energy exporters Europe relies on (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022).

According to Teppo Koivisto, Finland's total borrowing was 42.22 billion euros in 2024, slightly lower than the previous years, driven by government deficits due to economic conditions, but still shrinking slightly. The projection is anticipated to be even higher years after 2024 due to new policies for green transition targets, but Teppo Koivisto says that the Finnish economy will grow by 1.7% in 2025. (State Treasury Republic of Finland, 2024).

Although Finland's government has acknowledged the importance of stabilizing the debt-to-GDP ratio and practicing reducing borrowings, government initiatives to enhance investments towards battery storage solutions and building more renewable energy power plants during the year contradict their statement of strengthening government finances, which leads to more loans and higher debt. Following Finland’s accession to NATO, it has led to additional spending on defense in addition to green initiatives to align with the EU’s biodiversity. These are part of the broad overview of the debt areas and reasons to consider in trying to pay Finland’s debt (State Treasury Republic of Finland, 2024; State Treasury Republic of Finland, 2022).

This shows clear trends that Finland’s government might not be interested in closing down the debt and is likely to continue spending on some areas that might not satisfy individual people in a potentially economically growing country, or at least it will be delayed for many years.

Total Energy Supply (TES)	2016	2021
Non-renewable (TJ)	930 753	812 105
Renewable (TJ)	469 332	571 091
Total (TJ)	1 400 085	1 383 197
Renewable share (%)	34	41

Growth in TES	2016-21	2020-21
Non-renewable (%)	-12.7	-0.8
Renewable (%)	+21.7	+14.1
Total (%)	-1.2	+4.8

Primary energy trade	2016	2021
Imports (TJ)	1 062 967	850 684
Exports (TJ)	403 914	306 743
Net trade (TJ)	- 659 053	- 543 941
Imports (% of supply)	76	62
Exports (% of production)	55	39
Energy self-sufficiency (%)	52	58

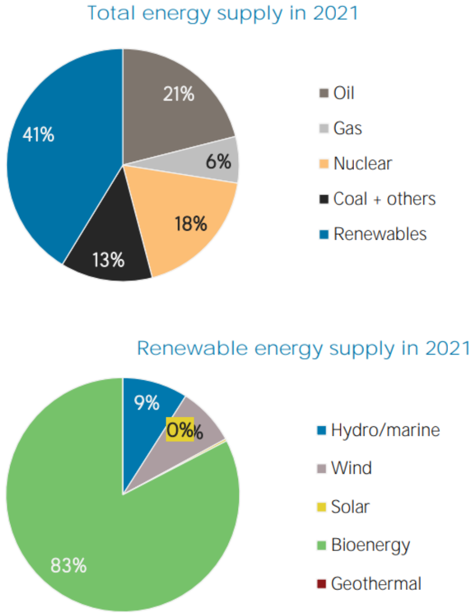


Figure 19. Total Energy Supply in Finland (IRENA 2024)

Observing Figure 19; In 2021, Non-renewables such as fossil fuels, peat, and nuclear sources cover 47% of Finland's total energy supply with 53% being from renewables like hydro, wind, solar, and bioenergy, with around natural 1% increased fluctuations each year forward, but also dependent on weather levels. The total energy supply from renewables was 571,091 TJ, compared to 812,105 TJ from non-renewables (IRENA 2024). Fingrid reports that renewable production will increase by 50% by 2030 compared to previous years (Fingrid, 2024).

Even with government initiatives increasing the renewable energy capacity with more solar, wind, and hydro plants, it will not be enough to reach the target. Below is the calculation of the realism of Finland’s goal post for carbon neutrality by 2035. Carbon neutrality means all energy must come from renewables; therefore, renewables must match the total energy production of 2030.

Equation 1. Calculation of Finland’s renewable energy production to reach carbon neutrality by 2035 using energy production data from 2021.

$$Total\ energy\ production\ in\ 2030:$$

$$(571{,}091\ TJ + 812{,}105\ TJ)1.5 = 2{,}074{,}794\ TJ$$

$$Production\ solely\ from\ renewable\ energy\ sources\ in\ 2030:$$

$$2{,}074{,}794\ TJ - 856{,}636.5\ TJ = 1{,}218{,}157.5\ TJ$$

$$Increase\ from\ 2030\ to\ 2035\ to\ reach\ carbon\ neutrality:$$

$$2{,}074{,}794\ TJ - 1{,}218{,}157.5\ TJ = 856{,}636.5\ TJ$$

$$\frac{856{,}636.5\ TJ}{1{,}218{,}157.5\ TJ} \cdot 100\ =\ 70.32\ \%$$

Finland has to produce renewable energy equal to the total of renewables and non-renewables production combined, which in this case is 2,074,794 TJ.
The question remains: Can Finland be independent from buying energy from other countries? The Finnish dream is to place itself on the list among the great countries without public debt.

Finland must produce 1.5 times more energy to reach energy neutrality without relying on imports, which is 2074794 TJ. If Finland successfully reaches the goal by 2035, it will also be able to produce energy without the need for imports (Statistics Finland, 2024). Finland's total average energy consumption is about 1,400,000 TJ (Statistics Finland, 2022).

To reach profit margins, Finland has to attain carbon neutrality by 2035 and produce enough energy that the country has energy in reserve to be one of the net energy exporters in the global market. Below is the calculation of the realism of Finland’s neutrality in production versus consumption in the coming years after 2035. To make passive profits, Finland has to produce more energy than it consumes, starting by matching the consumption rate.

Equation 2. The energy Finland must produce from renewable sources to neutralize total energy consumption after 2035.

$$Surplus\ renewable\ energy\ in\ 2035:$$

$$2{,}074{,}794\ TJ - 1{,}400{,}000\ TJ = 674{,}794\ TJ$$

$$Target\ surplus\ energy\ (to\ neutralize\ consumption):$$

$$1{,}400{,}00\ TJ + 674{,}794\ TJ = 2{,}074{,}794\ TJ$$

$$Required\ renewable\ energy\ production:$$

$$2{,}074{,}794\ TJ + 1{,}400{,}000\ TJ = 3{,}474{,}794\ TJ$$

$$Percentage\ increase\ required\ after\ 2035:$$

$$\frac{(3{,}474{,}794\ TJ - 2{,}074{,}794\ TJ)}{2{,}074{,}794\ TJ} \cdot 100\ =\ 67.48\ \%$$

Assuming that Finland has the same consumption in 2035 as in 2021, after reaching carbon neutrality, years after 2035, Finland would need to increase renewable sources further from carbon neutrality by 67.48% to be energy independent and start to make profits in the energy market.

The transition to renewable energy is expected to bring economic benefits through the Finnish government's ambitious investments in increasing the share of renewables. However, it is unrealistic to transition to only renewable energy production any time soon. It is not likely that Finland will achieve carbon neutrality by 2035.

Finland exported 24,120 TJ in 2021, which accumulated 377€ million euros in profit. 1 TJ was approximately 15588,77€ (Energy Authority, 2022). Below is the calculation of the realism of Finland’s profit margins in production after reaching carbon neutrality by 2035. At one point in the future, central banks must start paying the debt it has accumulated. Gross Domestic Product (GDP), which is the economic indicator measuring the total value of goods and services of a country's border within a year, electricity can be an innovative solution for Finland’s economic growth.

Equation 3. The amount of electricity needed to export to repay 15 billion in debt loans annually.

$$\frac{15{,}000{,}000{,}000\ €}{15{,}588.77\ €\ per\ TJ} \approx\ 962{,}169\ \text{TJ every year}$$

For Finland to repay about 15 billion in debt loans every year, Finland has to produce about 962169 TJ every year.

Finland's energy landscape undeniably constitutes a complex correlation between ambition and realism. The need to ramp up production underscores the challenges in achieving energy independence and profiting in the energy market. Moreover, the financial and economic consequences of Finland’s shift towards the renewable energy production model cannot be overlooked, as the country's ability to repay its debt hinges on the success of energy production each year. Despite these challenges, with strategic investments and innovation, Finland still has the potential to navigate through these complexities and adopt unique sustainable practices in the renewable energy sector.

4 Methodology

The research conducted in this thesis is done by applied research utilizing 3 CSV files containing a total of the past 9 years of historical data from 2015 to 2024 about Finland's weather on four factors (air temperature, cloud cover, precipitation, and wind speed) for predictive modeling. Additionally, it incorporates historical data on energy consumption trends influencing the potential future energy production rate. The data has been downloaded from Finland’s open weather data source Finnish Meteorological Institute (Finnish Meteorological Institute, 2024). The data has been trained and tested using Python machine learning gradient boosting techniques XGBoost and LightGBM. The generated forecasted chart extends 10 years ahead. The charts show the results of regression, showing a continuous output predicted. This research aims to determine with visual analysis whether climate change is increasing or decreasing and whether Finland can benefit from climate change or global warming in the coming years for higher energy production moving forward.

Important variations in air temperature, cloud cover, precipitation, and wind speed characterize Finland's weather, influencing the output and efficiency of energy production systems. This study groups an extensive dataset reflecting the sophisticated Finnish climate by data sourced from the Finnish Meteorological Institute. This dataset could provide a footing for how environmental parameters affect energy production in the coming years.

XGBoost and LightGBM were chosen for their ability to deal with large and complex datasets. Other modeling methods were practiced with ARIMA, Seasonal AutoRegressive Integrated Moving Average (SARIMA), and time series analysis, but due to non-stationary reasons, forecasted data were not accurate. This is because these models need long-term periods of data, the general direction of data, and fluctuations that occur during specific intervals. ARIMA assumes that past values influence current values, removing trends and seasonality. It is sensitive to outliers and non-stationarity, becoming less effective for seasonal patterns. SARIMA on the other hand has the same issues but is the better option of the two regarding weather forecasting since it is an extension of ARIMA incorporating seasonal components from daily and monthly temperature variations making it flexible in modeling complex temporal dependencies. It can be used to determine both non-seasonal and seasonal patterns, but aside from a long period of historical data like ARIMA, it still requires clear seasonal trends. Gradient Boosting can sometimes outperform both ARIMA/SARIMA due to their ability to capture non-linear relationships. Gradient boosting overall excels in regression tasks (Bajaj, 2023; Majka, 2024). These models have various features that handle weather parameters on predicted outcomes. They align with this study's objective to visualize and analyze climate change effects, making it easier to approach the findings and draw conclusions about benefits for Finland's energy sector.

The simulation leverages empirical data on total electricity consumption in Finland across all sectors (commercial, residential, and industrial) and renewable energy production, specifically from solar panels, hydro plants, and windmills. Weather uncertainty presents an opportunity for Finland's energy sector through the benefits of global warming towards energy production with rising temperatures or reformed precipitation patterns. Contrariwise, it also comes with risks if the patterns show extreme levels, which could burden energy generation by changing everyday consumer consumption patterns. By forecasting energy production based on historical weather data and trends, the findings will enhance the understanding of climate change implications supporting the country's transition towards a sustainable energy future and economic growth.

4.1 LightGBM and XGBoosting

LightGBM (Light Gradient-Boosting Machine) uses tree-based learning algorithms known for their speed, accuracy, and efficiency. LightGBM employs a gradient-based one-sided sampling technique when handling large datasets fast and accurately, a method that keeps all the instances with large gradients and randomly samples instances with small gradients. LightBGM has a smaller memory footprint than XGBoost. XGBoost (Extreme Gradient-Boosting) is an open-source software library and offers various advanced functionalities such as handling missing values, tree pruning, and cross-validation, which LightGBM lacks. This feature allows XGBoost to calculate outlier forecasts, a vital step in many machine learning tasks. Both XGBoost and LightGBM are categorized in gradient boosting, which is a machine learning method of weak learners (decision trees) used to improve the model beyond random guessing or chance, and their performance is improved by interpreting the decision trees to output the combination of the weak learners for a total better result (Saha, 2024).

Gradient boosting filters out instances that are hard to predict accurately by developing weak learners to handle them. Weak learners are components of gradient boosting that improve the model's ability to learn from the data and ensemble methods of the prediction. The model is trained with the whole 9-year dataset from actual values and prediction values calculated to make an error in between. More weight is given to the incorrect predictions while the new model (LightGBM) attempts to fix the error (Saha, 2024).

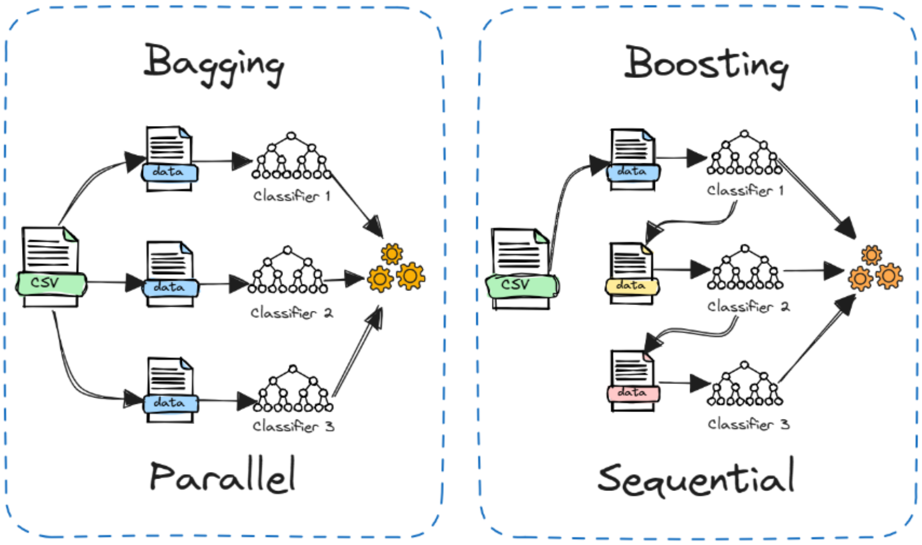


Figure 20. Gradient boosting assembly of models is known as bagging and boosting (Radar, 2023)

Figure 20 illustrates the difference between bagging and boosting. XGBoost is controlled by the learning rate, leveraging rows and columns. XGBoost is highly efficient with a short-time scale data compared to other models that need decades of data to forecast accurately. XGBoost works well with sparse and adapts to multiple types of input data.

It is precise and the second fastest gradient boosting library after LightGBM. The algorithm that builds a strong model by combining the predictions of several weaker models is generally a decision tree. The forecasted charts show that the general model variance decreases significantly due to bagging, but the bias also decreases with boosting (Radar, 2023). Bias refers to the error introduced by assessing a real-world problem. The model uses dependency analysis, exploits effects between learners, and reduces error by averaging the results. In bagging, it combines multiple models to reduce variance by creating subsets of the data through random sampling. It then trains each subset and combines the outputs, decreasing the variance of the final prediction, which improves predictions (Hachcham, 2024; Saha, 2024).

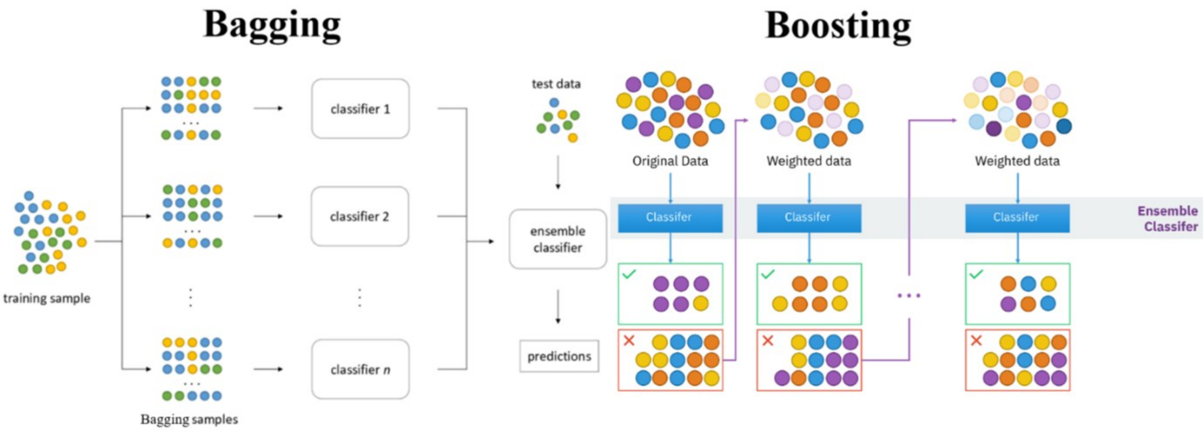


Figure 21. XGBoosting intuition behind the bagging and boosting algorithm (Hachcham, 2024)

The illustration in Figure 21 about XGBoosting shows how it sequentially builds on the weaknesses of previous models. It improves the weak learners by training the best possible model variations, where each new tree corrects the errors made by the previous ones. It learns from non-linear relationships in data patterns due to the nature of decision trees by capturing them, while avoiding overfitting, instead of relying on random guessing by specifying the weighted subset of the data (Hachcham, 2024). The subsets that will get misclassified earlier will get higher weights, and combined weighted sums will be used for classification or ‘regression’.

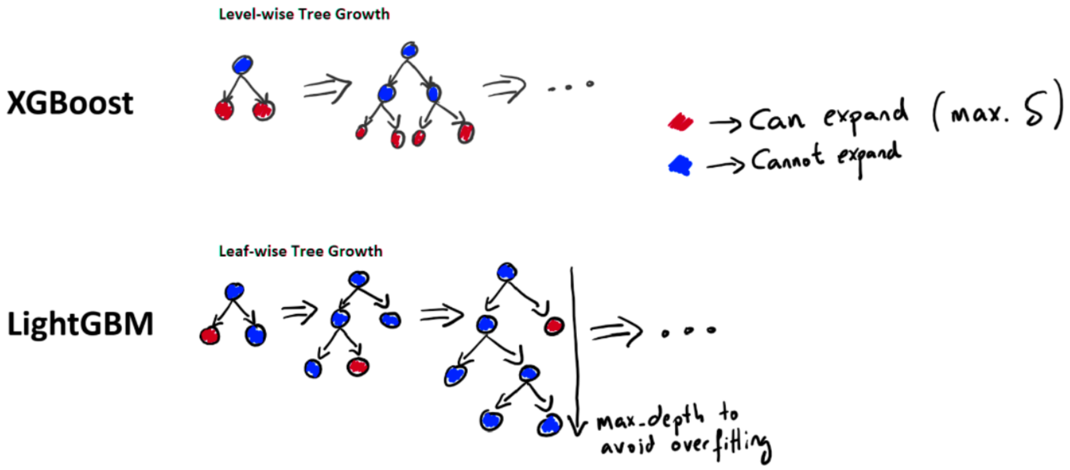


Figure 22. The difference between XGBoost and LightGBM

Represented in Figure 22, LightGBM handles splits, while XGBoost evaluates frequency or weight when calculating particular times in the models, but is prone to biases when handling large datasets. LightGBM handles large datasets and is known to be above XGBoost in terms of speed for training and predictions, but has less comprehensive capability. They both solve similar problems. While XGBoost has a horizontal growth, LightGBM carries a vertical growth, leading to higher accuracy due to loss reduction. LightGBM is the less robust of the two due to the overfitting of the data. Both algorithms perform well; however, LightGBM is faster because it does not use specific weights for the data (Saha, 2024).

XGBoost expands the first level of the tree and continues to the second tree after finishing the first. LightGBM, on the other hand, does not intend to finish the trees before the next. Both grow to be full trees. Overfitting means that it applies early stopping criteria or post-pruning. Both models build different trees, due to leaf-wise trees converging much faster, but contributing to global loss, potentially overfitting the data. Level-wise splits contribute to the loss of particular branches, and in the sampling process, repetitions are possible (Saha, 2024).

4.1.1 Mathematical formula

Using a time series analysis paired with gradient boosting to predict future values, the data preprocessing and cleaning steps combine the 3 CSV files and prepare them to be analyzed. The code converts the time column into a date-time format and sets it as the index.

- **Dropna**: The chosen weather factor is converted into numeric format. The columns of the rows in non-numeric entries are dropped.

The code's next step generates time-based features like hour and month for seasonality analysis. The rows with missing values (**NaN values**) are discarded completely to populate the dataset for analysis.

- **Data libraries: NumPy** and **Pandas** are used for manipulating numerical operations. **Matplotlib** is used for data visualization. **Scikit-learn** is used for training, testing, and splitting the data from model selection.
- **Gradient boosts:** XGBoost and LightGBM build and evaluate the model. Model training and evaluation separate x from variable y for time-base features created in the earlier steps, and the train-test split performs with a test size of 20%, without shuffling.
- **Fitting:** The models implement regressors with 1000 estimators and a learning rate of 0.01 to balance the training speed and model depth, a process called fitting. Each model predicts values on the test set and generates a future time index.

After importing all necessary libraries to run the code, the data is processed so that the cloud cover, air temperature, precipitation, and wind speed are readable. The data is resampled into months. The existing data is plotted for reference, and the features are created for the model languages. The data is split into training and test sets, then models are fitted to the training data. After training the data, it is evaluated by printing R^2. The features are created for future prediction to use the model to forecast future values. The forecasted results are plotted alongside the original data.

Formula (1) is known as the arithmetic mean formula. It defines the calculation of the mean average in statistics. This thesis utilizes it to find the average wind speed, precipitation, and temperature. It sums all the observed numbers in a series in a group and divides them by the count of all observed numbers in a series (Geeksforgeeks, 2024).

$\boldsymbol{\gamma_{true}}$ **:** Actual observed dataset values from the target variable.

$\boldsymbol{\gamma_{pred}}$ **:** Predicted values generated by the regression model.

$\boldsymbol{\gamma_{act}}$ **:** The mean average of the observed value $\boldsymbol{\gamma_{true}}$

$$\gamma_{act} = \frac{1}{n}\sum_{i=1}^{n}\gamma_{true,i} \tag{1}$$

The formula (2) represents the evaluation metric **R²** score ranging from 0 to 1. It takes a segment of the conflicts of data points from dependent (predictable) and independent values, finding the best fitting line from regression analysis. It visualizes the relationship between the values. The higher the **R²** values, the lower the 'unexplained', errors or residual variations, meaning the model fits the data well and makes it easier to make accurate predictions (Fernando, 2024). Figure 23 shows an example of a visual illustration of scatter points around the regression line that has been adjusted to align values with the observed values.

Figure 23. Visual representation of R^2 in regression and fitted line plot (Frost, 2024)

There is more variance in the regression models when data points are closer to the line. This means R^2 with less % would be scattered all over the graph. Data points closer to the line are considered good. Curved regression lines often under- and over-predict the data points across the curve, leading to specification biases. Bias occurs only when linear models lack considerable independent variables (Frost, 2024).

$\sum(\boldsymbol{\gamma}_{\boldsymbol{true}} - \boldsymbol{\gamma}_{\boldsymbol{pred,test}})^2$ **Numerator** represents how far the total residual squared difference is between actual and predicted values. It sums up the total residual values in the model; the true values are subtracted from each predicted value.

$\sum(\boldsymbol{\gamma}_{\boldsymbol{true}} - \boldsymbol{y}_{\boldsymbol{act,test}})^2$ **Denominator** presents the total squared difference between actual and mean actual values; the total sum of squared indicates the total variance of the target value. It sums up the total of the explained values in the model; the true values are subtracted from each actual value.

$$R^{\mathbf{2}}{}_{\boldsymbol{XGB\ or\ LightGBM}} = \mathbf{1} - \frac{\sum(\boldsymbol{\gamma}_{\boldsymbol{true}} - \boldsymbol{\gamma}_{\boldsymbol{pred,test}})^2}{\sum(\boldsymbol{\gamma}_{\boldsymbol{true}} - \boldsymbol{y}_{\boldsymbol{act,test}})^2} \tag{2}$$

By dividing the numerator and denominator, we get the total residual difference by the model. Subtracting the result by 1, we get the total difference explained by the model. It assesses regressor model performance by measuring the number of variances captured by the predictions. Value 1 indicates that the model perfectly predicts the target variable, whereas 0 does not define the variances; it predicts the mean, independent of the input features. The final step of the code displays predictions made by both models on the graph alongside the actual data (Fernando, 2024).

5 Empirical analysis and results (Simulation Implementation)

The XGBoost method in Figure 24 is highlighted in green, providing a forecasted estimation of how the years following 2024 will unfold. The LightGBM method in the chart is highlighted in yellow and attempts to fix the error made by XGBoost.

These models indicate that, although there are no substantial fluctuations with gradient boosting different from the historical data, it is crucial to understand that analyzing long-term climate trends aids in planning and investment decisions on renewable sources infrastructures. This facilitates resource allocation and provides energy providers with consumers the opportunity to save money on their energy bills by understanding energy demand patterns during peak periods.

The visualization forecast of Finland was produced using both XGBoost and LightGBM machine learning models. Historical data was resampled into 1-hour intervals and mean electricity consumption for each hour. Below is the chart of electricity consumption projections for the next decade.

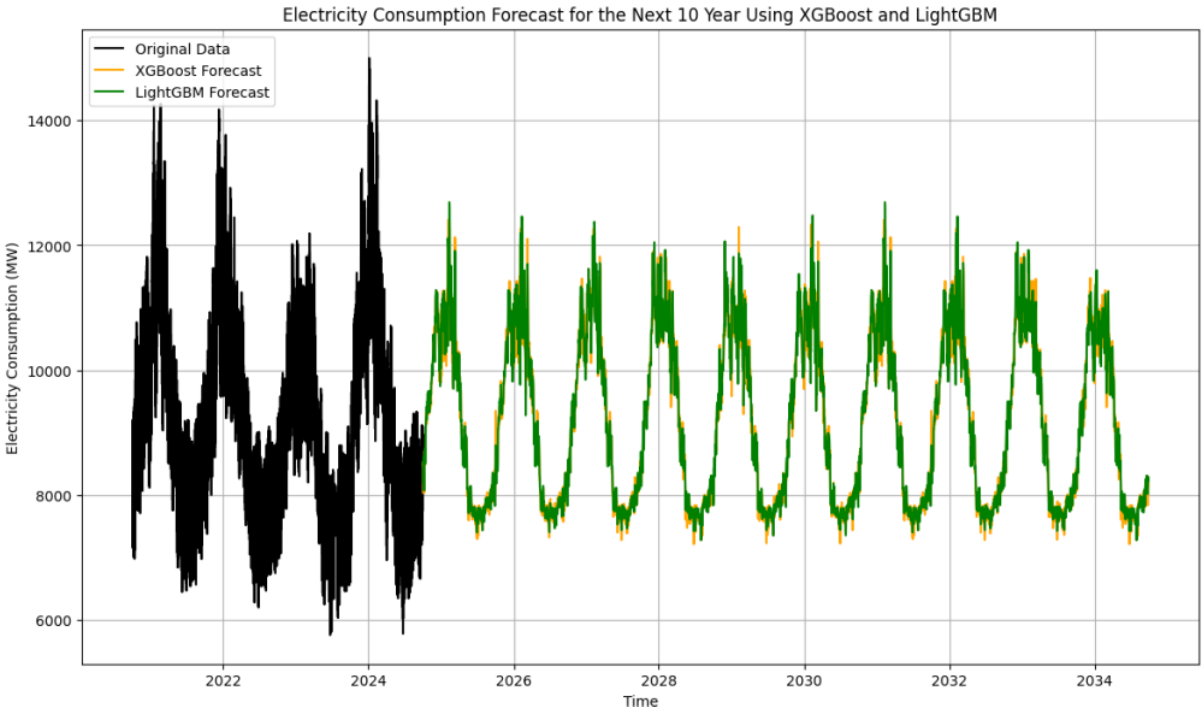


Figure 24. Forecasted electricity consumption 10 years ahead in Finland (Fingrid, 2024)

Four major factors affect the consumption data that cannot be forecasted: economic growth, weather changes, technological advancements, and population changes, making the prediction nonstationary. The forecast data helps optimize peak demand periods and purchase energy at low rates. The year-ahead data can still help with applying solutions in energy distribution optimization during peak demand periods and managing grids with anticipated fluctuations. The chart shows that energy consumption will grow in the next 6 months, especially in the wintertime, decrease in the summer season, and afterward stabilize. Comparing 2024 data to the forecasted 2025, it can be assumed that the rise of renewable energy implementation will have environmental benefits and economic growth as consumption continues to plummet. The future of Finland is looking bright from the supply-demand perspective, considering the government designs policies and regulations programs to reduce consumption during peak times and balance the load.

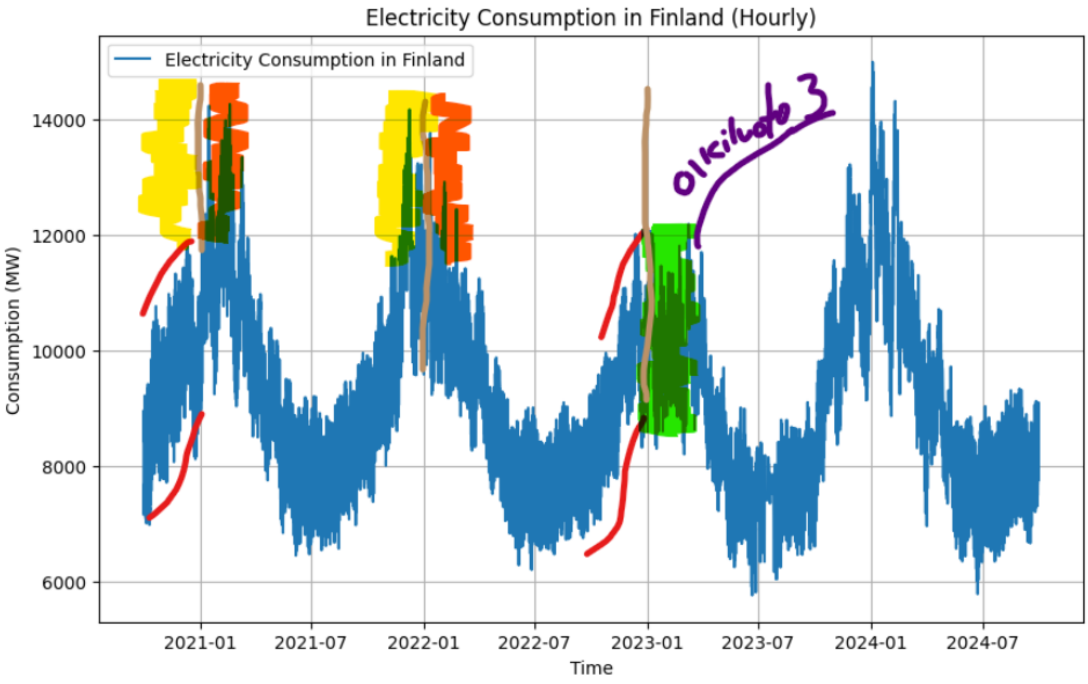


Figure 25. Electricity Consumption in Finland (Fingrid, 2024)

It is hypothesized that since the Russia-Ukraine war started, the Finnish parliament changed its April 2023 initiatives, and regulations increased the electricity prices around the country during 2021 and 2022. However, when the government changed and the war became less mainstream, electricity prices were lowered, making Finnish citizens more confident in purchasing energy. In 2023, the Olkiluoto 3 nuclear power plant was completed, contributing to 15% of Finland's electricity consumption in April (Wikipedia, 2024; State Treasury Republic of Finland, 2023).

Figure 26 shows the Finnish population's annual growth rate. Finnish population growth has been declining, and the electricity consumption is not a significant factor, particularly in Finland.

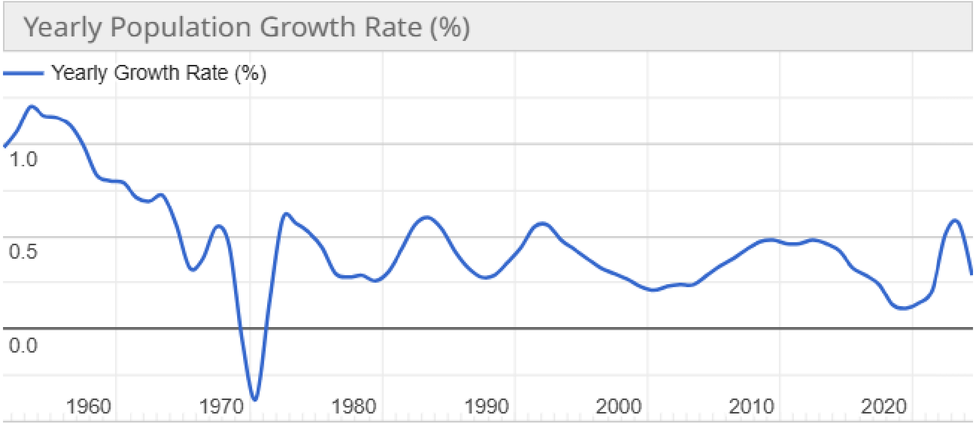


Figure 26. Historical chart of yearly population growth rate in Finland (Worldmeter, 2024)

The chart shows that the Finnish population has declined since 2022. It can be inferred that the reduction of energy used on human resources such as electric vehicles and house utilities decreases, also leading to a demand drop for residential, commercial, and public buildings, amounting to more electricity reserve for the whole country; an indication that reliance on electricity imports from neighbouring countries also are reduced. The decline of the population may encourage innovation, maintaining productivity with fewer resources. The Finnish government has set an energy plan to allocate resources nationwide and install more solar and wind power. Meanwhile, urban areas could see investments promoting higher energy efficiency.

5.1 Finland's Climates: Wind, Rain, Clouds, and Temperature Trends

Figures in this chapter project the average temperature over the next 10 years. The trends in the following graphs illustrate the importance of weather forecasting adaptation for renewable energy generation in Finland using AI and machine learning. The forecast has been optimized to show the estimated average wind speed, precipitation, air temperature, and cloud cover.

The dataset consists of weather observations from the station "Vaasa Klemettilä" ranging from 2015 to October 2024, covering 10 years of the following data and columns:

- Observation station
- Year, Month, Day, and Time [Local time]
- Air temperature mean [Â°C]
- Cloud cover [1/8]
- Precipitation amount mean [mm]
- Wind speed mean [m/s]

5.1.1 Wind speed forecast

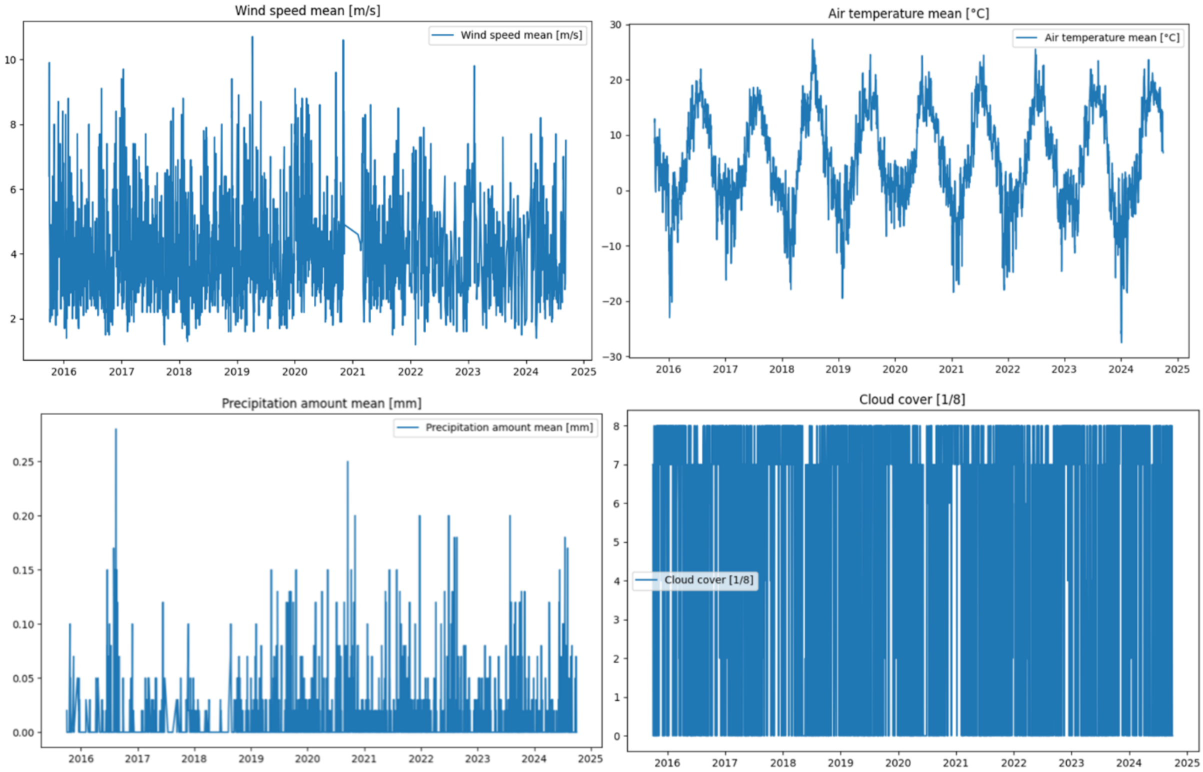


Figure 27. Original daily data of Finland's wind speed [m/s], air temperature [°C], precipitation [mm], and cloud cover [1/8] from 2015 to 2024 (Fingrid, 2024)

Figure 27 above shows the graphs of 4 weather factors with daily data. The daily data on cloud covers could not be comprehended by the code, due to its requirement to be converted into months and the removal of the fraction '[1/8]'. This is why all of the original data implemented in the graphs were converted into months for the predictions to be more accurate.

Figures 28 and 29-31 show the result of the conversion from the daily average to the monthly average. The yellow XGBoost and the green LightGBM show the average mean forecast for the next 10 years using the monthly converted previous data.

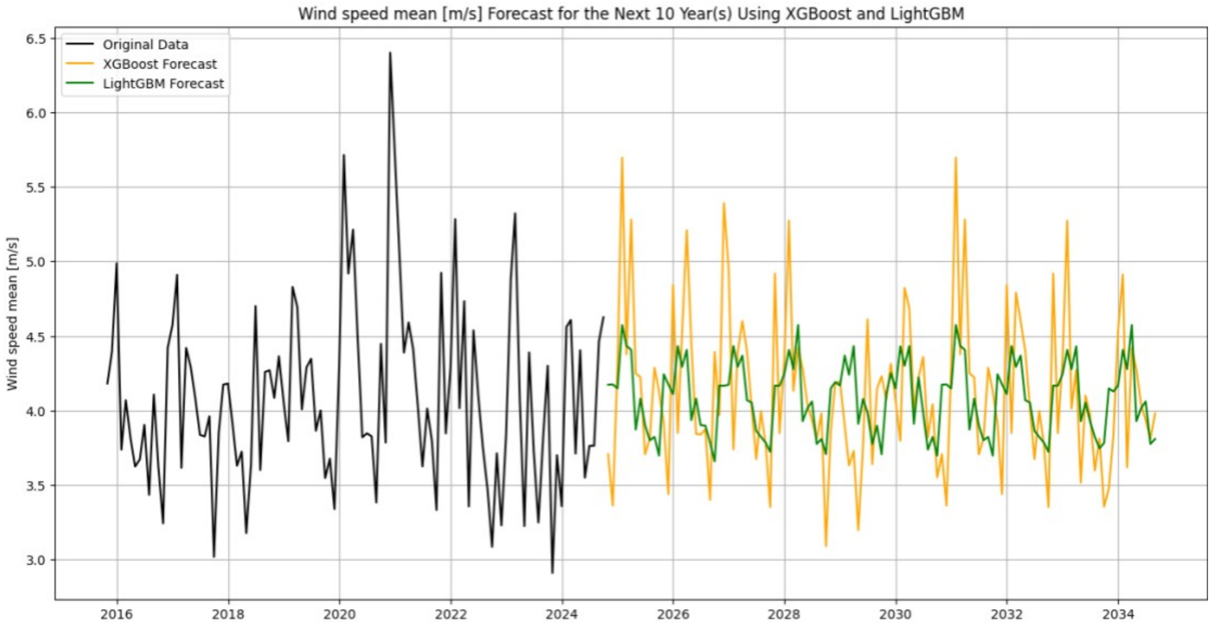


Figure 28. Forecasted wind speed [m/s] 10 years ahead in Finland in months (Fingrid, 2024)

Figure 28 shows the wind speed prediction within the next 10 years. The prediction is rising in the lower parts, while in the latter parts, the spikes equalize, leading to fewer sharp increases in wind speed. They could still fluctuate more within the months. There will still be variability across shorter timescales, and it will be challenging for grid management and complementary storage solutions to manage supply and demand.

Between historical data and forecasted data, the wind speeds are increasing in spring–summer seasons from averages of 5 [m/s] to 5.5 [m/s] on the high ends, and from the low ends of spring–summer seasons stay the same at averages of 4.5 [m/s]. Autumn seasons will have an increase averaging from 3 [m/s] to 3.5 [m/s]. Wind speed has a clear potential for wind energy generation during these seasons.

Low-speed regions with new technologies could capitalize on lower wind speeds that would not be optimal for all turbines. The optimal wind speed for all turbines is 4.0 [m/s] and for small utility-scale wind turbines 5.8 [m/s] (Eia, 2024). This suggests that most wind energy infrastructures need to be optimized seasonally, with springs and summers being the key periods for peak production, and with the help of advancing new technologies to enhance capture during autumn.

Since the wind speeds show an increase in the trend, it might be a good sign to upgrade energy storage solutions and grid integration to handle fluctuation and produce excess energy.

Figure 29 shows a graph of wind turbine output per m/s. It suggests that too much wind speed decreases the turbine's potential. Maximum output is produced around 12-15 m/s.

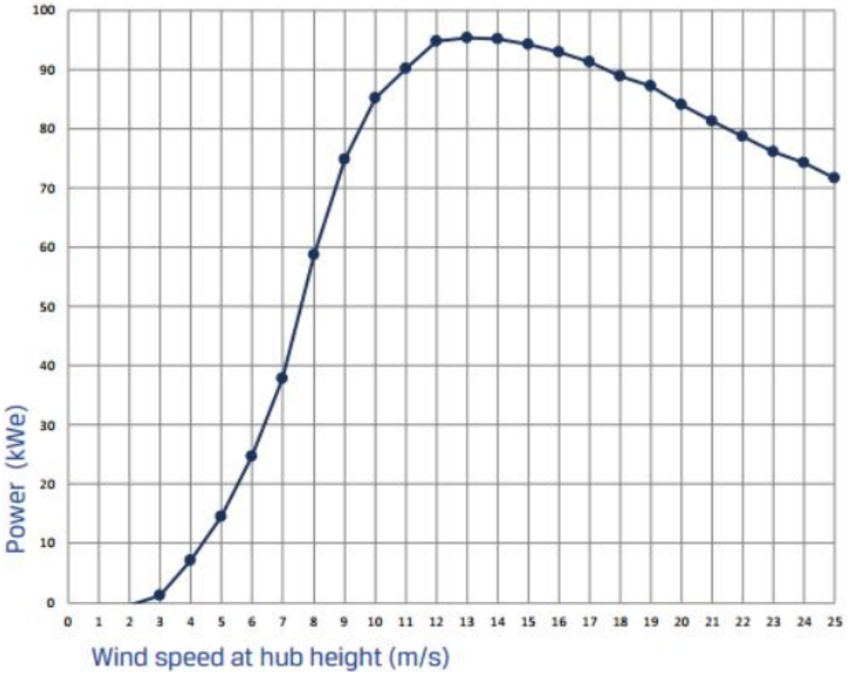


Figure 29. Wind turbine output power curve per m/s (PennState, 2024)

Formula (3) has been used to calculate the following statements: According to PennState (2024), the wind speed power output difference between 6 m/s and 12 m/s is an 8 times difference, only being double the speed. If wind turbines are optimized to generate power beyond 15 m/s, for example, 18 m/s, the generation would be 27 times larger than what can be produced from 6 m/s. Various factors affect the power curve of wind turbine output, such as specific turbine design and starting speed (PennState, 2024).

- Power = Watts
- ρ (rho) = density of the air in kg/m3 = 1.225 kg/m^3
- A = cross-sectional area of the wind in m^2 = 452.4 m^2
- v = velocity of the wind in m/s

$$(\boldsymbol{W}) = \frac{\mathbf{1}}{\mathbf{2}} \cdot \boldsymbol{\rho} \cdot \boldsymbol{A} \cdot \boldsymbol{v}^3 \tag{3}$$

Wind energy is one of the largest renewable sources that can help reduce dependency on fossil fuels with its spurred higher wind speeds. Higher wind speeds have a potentially small effect on water systems, helping in additional hydropower generation by affecting water flow. In addition, wind influences water evaporation rates, which impacts water availability for hydropower generation. This won't be an issue in Finland as it is not an arid region. Instead, wind speed would increase the precipitation levels, accelerating snowmelt speeds Rain-on-snow) leading to more water availability. The combination of wind speed and increased solar radiation may decrease Finland's water availability in the future (Mazurkiewicz et al., 2008; National Park Service, 2019; Van der Valk et al., 2021; Wirangga et al., 2023).

Although the increase in high wind speeds associated with broader climate shifts, such as storm intensity, could be a risk for infrastructures and ecosystems, Finland is not expected to see massive changes for many years, according to the wind speed prediction graph above. Finland can benefit from infrastructure investments in next-generation wind turbines operating at diverse wind speeds. This holds significance as seasons vary with forecast changes. Wind speed isn't rising much on the higher spikes during peak seasons, indicating that there isn't a significant chance of utilizing winds or wind turbines much more anytime soon compared to the previous 9 years.

The gradual increase in wind speed at lower levels is a promising trend, suggesting that wind energy is becoming steadily available even outside of peak seasons, reducing dependency on fossil fuels during low-demand periods. There is limited growth in the peak wind speeds, while remaining relatively constant, which may indicate a limitation of potential maximum output from wind energy during the high-demand or peak seasons. Wind production is unlikely to be a significant contributor within the next decade. Therefore, other renewable energy sources should be integrated into the pursuit of Finland's zero-emission goal process.

5.1.2 Air temperature

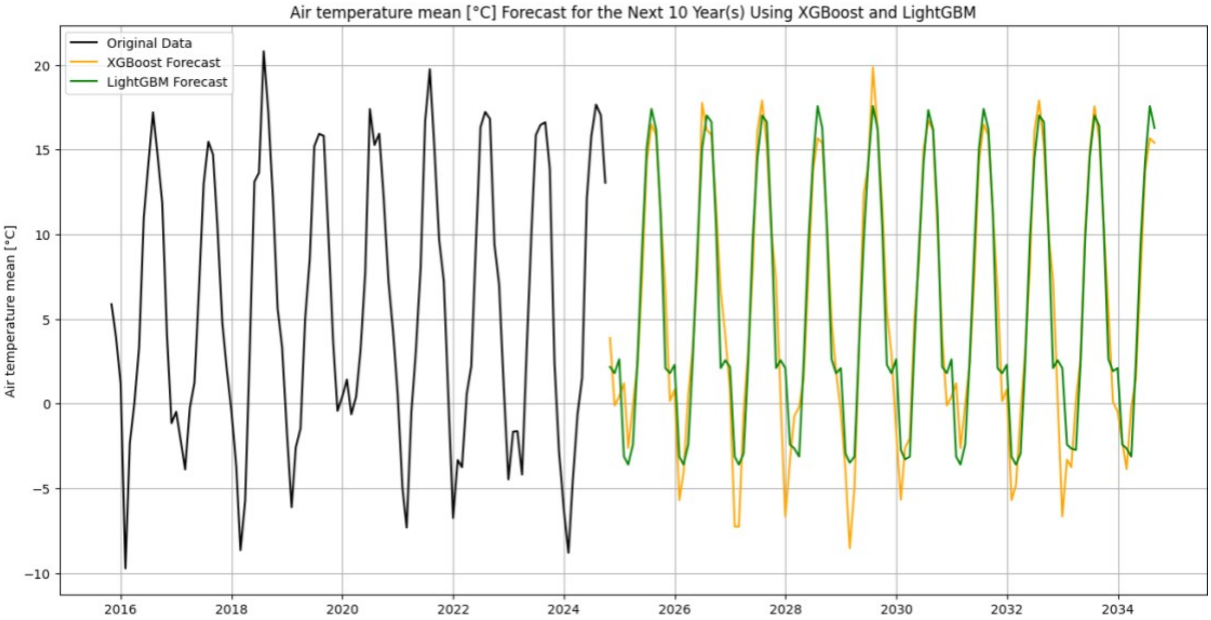


Figure 30. Forecasted air temperature mean [°C] 10 years ahead in Finland in months (Fingrid, 2024)

Figure 30 shows the forecasted air temperature within the next 10 years, where high-end temperatures are not rising considerably, instead, showing a modest upward trend following a particular pattern. This means that Finland may experience warm days commonly. Typically, solar panels are most efficient during moderate temperatures. The most efficient operating temperature is between 15°C and 25°C. After 25°C, it will gradually lose its production efficiency (SolarCC, 2024). Low temperatures do not affect the solar panel systems negatively, instead, they will reduce electrical resistance, allowing for higher electrical output (Noor, 2024). Finland's cold weather average range of -10°C to -5°C will be beneficial. Aside from optimal temperatures and excluding Finland's high latitude on Earth, cloud cover will be the crucial factor determining the solar panel energy generation optimization. Solar panels may remain viable as temperatures aid in their operation. The gradual increase could influence the demand for house cooling during the summer. This could introduce new seasonal peaks in electricity demand. Low-end temperatures imply that Finland will see milder winters, shifting to reduced heating demand during high-demand winter times, reducing strain on grids. This is positive to Finland's goal towards decarbonization as it would lower fossil fuel use in heating.

Low-end temperatures also affect wind patterns and speed, potentially leading to constant wind energy production. Temperature gradients are higher during the winter. Winds are developed when air moves from high to low pressure, leading to rapid air flow. This is due to the heat in the land, and the water being heated unevenly (Eia, 2023). Higher wind speeds benefit solar power efficiency as wind speeds of 1 m/s could cool solar panels by 5°C to 11°C (Noor, 2024). In cold months, less winter storm severity leads to fewer disruptions and more predictable wind energy outputs.

There is a debate among researchers about whether the air temperature has a positive impact on hydropower energy production. Higher winter temperatures melt the snow cover, which leads to higher water levels during autumn. During warm days, it evaporates water levels, leading to less water availability for energy production in spring.

The projection suggests that there may be a shift in Finland's overall climate, ecosystem, agriculture, and natural resources. This could result in shorter winters, while summers are becoming longer, which might extend growing seasons supporting agriculture. Although the temperatures look moderate, they could alter Finland's energy and climate landscape. Energy storage and grid management will have a chance to change for more seasonal variability, as the temperature trend shows a positive shift toward sustainable energy use.

5.1.3 Precipitation

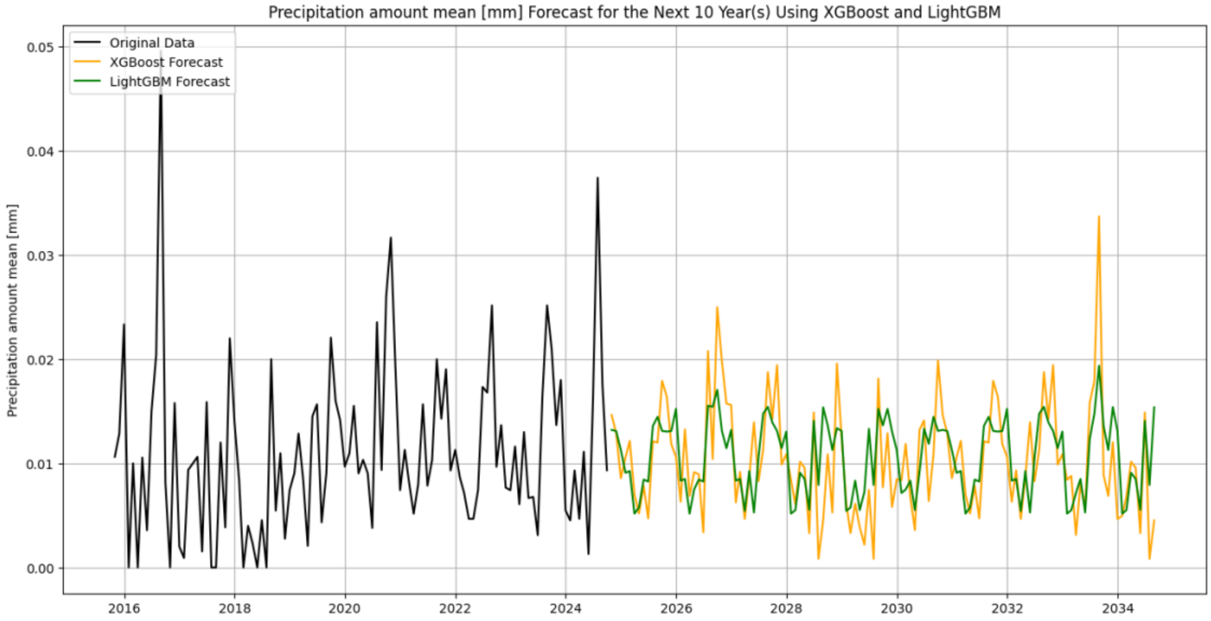


Figure 31. Forecasted precipitation amount mean [mm] 10 years ahead in Finland in months (Fingrid, 2024)

Figure 31 shows the forecasted precipitation within the next 10 years. Precipitation prediction levels in the first few years follow the same average trend in historical data. Patterns change to reduced levels from high-end peaks of 0.05 mm – 0.04 mm during the summer to the autumn season and averages of 0.03 mm to peaks of 0.035 mm and averages of 0.02 mm; a sign that precipitation gradually decreases from harsh rains to moderate levels leading to less agricultural damage, flooding, damage on dams or water channels, improving the hydropower plant stability. However, water for reservoirs might decrease as water availability lessens due to fewer high-precipitation events, limiting hydropower output, especially during dry seasons (Soomro, 2024).

Precipitation levels might have little direct impact on wind energy, where drier climates correlate with changing wind patterns; the study from the University of Nottingham researched that the fewer storm-related wind surges, the more turbine reliability is improved, and maintenance cost is reduced (Al et al., 2011).

Looking at the chart more closely, the spring to early summer seasons have more days without rain, with precipitation levels nearing 0.00. At the same time, predictions show that there will be fewer days without rain and minimal precipitation levels of 0.005 mm. Although near the average to zero precipitation levels, fewer rainy days from spring through summer could lead to extended dry periods. Reliance on hydro energy storage solutions would balance the renewable supply's fluctuating energy demand. Frequent light precipitation levels may help sustain hydropower reservoirs without straining the ecosystem.

In contrast, as Finland is shifting towards patterns of minimal rainfall leading to possible long dry periods, infrastructures such as drainage systems, retention ponds, sewer systems, and roadways may not be adequately equipped to manage the cumulative effect of these lighter rains over time. Instead, they should be re-evaluated and designed to adapt to more frequent light to moderate rainfall. This will reduce the stress on water dependency towards the ecosystem and agriculture, potentially affecting healthy crop yields, sustaining biodiversity, and ensuring food security (Cybersecurity and Infrastructure Security Agency, 2024; Palermo, 2024).

For the next 10 years, the differences in precipitation levels are minimal compared to the historical data and are unlikely to change dramatically. Therefore, Finland’s vegetation will mostly remain unchanged and may realize slow-paced progress.

Light precipitation during winters might mean less snow accumulation and more rainfall, both crucial for hydropower generation during the spring, particularly when snowmelt dynamics are impacted (Soomro, 2024). The solution would be to mitigate potential hydropower reduction by capturing and storing rainwater for circular water management for reuse during light rainfall events and upgrading water drainage to manage drought periods (Ministry of Agriculture and Forestry of Finland, 2022; Palermo, 2024).

5.1.4 Cloud cover

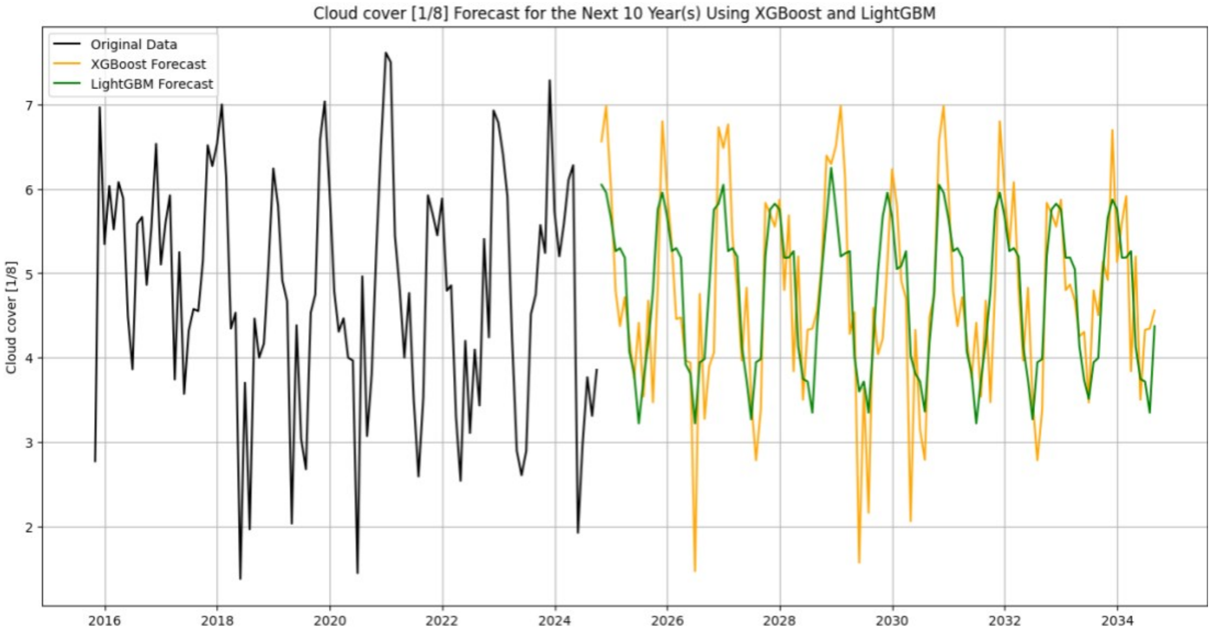


Figure 32. Forecasted cloud cover [1/8] 10 years ahead in Finland in months (Fingrid, 2024)

Figure 32 shows the forecast of cloud cover within the next 10 years, where the prediction shows high average fluctuations around [~7/8] during winter times and between [~1.5/8] – [~3.5/8] during the summer season. Summers show low and stable cloud cover, allowing optimal solar energy generation. While on the lower bounds, it might slightly reduce generation during the later years, it is still expected to have minimal impact.

Finland could create an opportunity and capitalize on solar energy by building more solar panels to boost the possible storage of excess energy from warm months for harsh winters. In contrast, a consistently high cloud cover signifies limited solar radiation, making it a less feasible option for the winter season. Finland would have to rely on renewable sources like wind and hydropower to balance the energy production in this season.

Historical data show average spikes above [7/8] during winters, but summers closer to [~1.5/8] – [~3/8], an indication that cloud amounts are relatively the same throughout the first 5 years. The low-end last parts of the forecast show a pattern change from [~3/8] to [~3.5/8] during the summer season, while keeping the same levels in the winter.

Since landscape temperature increases due to solar rays with less cloud covering it, water availability is expected to be low in the first 5 years. As the cloud cover pattern changes to moderate levels, water availability will increase for hydropower capacity due to less heating.

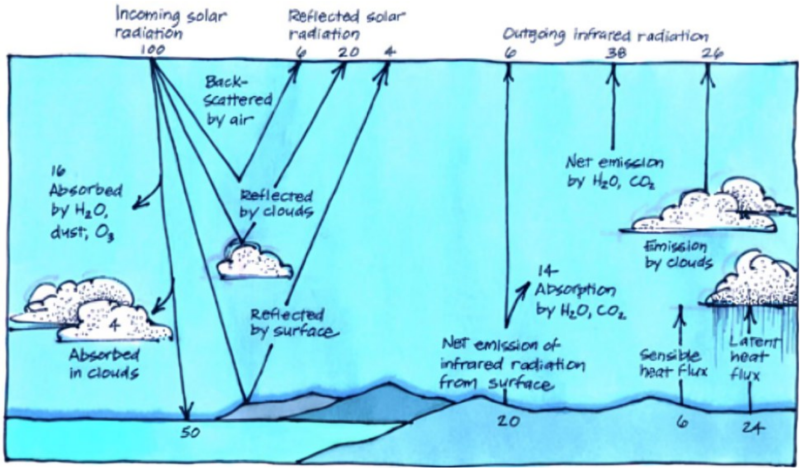


Figure 33. The energy absorbed, reflected, or transmitted by clouds (National Oceanic and Atmospheric Administration, 2024)

Figure 33 shows an illustration of how cloud cover affects the atmosphere. High wind and cloud cover during winter could trap heat that will moderate cold temperatures, leading to reduced demand for heat. Still, it will have a downstream effect on the ecosystem and water availability for hydrological cycles. These effects may cause a decline in snow accumulation and shift spring melt patterns because warmer temperatures mean less snowfall, as higher humidity from solar radiation in warm seasons would accumulate clouds (Graham, 1999; Harpold & Brooks, 2018).

Persistent high cloud cover during early-midwinter may lead to rain dominance rather than snowfall, particularly in Finland, where the cloud would not be too hot or cold in the future, but cold enough to release raindrops (Graham, 1999; Harpold & Brooks, 2018). One would consider that persistent high cloud cover also reflects and lowers solar radiation output from reaching the surface, slowing down snowmelt. However, researchers have found that cloudy grey winters trap heat during cold times, making ice thinner and warming up snow faster, increasing water availability (Patrick et al., 2015; Brooks et al., 2018).

Rising thick summer clouds act as covers or ‘blankets’, reflecting solar radiation and returning it to space. This may cool down warmer months, as there will be less sunlight exposure on the landscapes, saving energy on building cooling systems. This also has a positive impact, as too much solar exposure in vegetation and agriculture could affect evapotranspiration rates. Higher summer clouds would potentially be beneficial for water retention in soils. What little water is evaporated will be returned by the rivers (Irmak, 2017; ISCCP, 2024).

Long-term monitoring and climate adaptation are crucial as the first 5 years suggest a stable window for adaptation and energy planning. The pattern changes in the later years could signal a gradual shift in atmospheric dynamics. Based on the output of the cloud cover, winters should focus on wind and hydropower as primary energy resources during this time and focus on investing in energy storage systems to counterbalance the low solar potential. The summer season maximizes solar energy generation due to low cloud cover.

Finland should embrace utilizing fossil fuels to warm the country and allow change to happen. This will enable it to derive most of its power from renewable energy sources, while enhancing grid infrastructure and energy storage technologies over the next 10 years to reach its desired milestones and zero-emission goals. As renewable sources show prominent results, emissive sources should be proportionally reduced to offset their increase.

It is important to note that monitoring changes to cloud cover interaction with precipitation and air temperature trends on water management resources and their effectiveness towards agricultural productivity should also be a priority, as it all has a chain reaction to social and economic quality to reach energy independence. A slight upward trend in the later years of summer cloud cover is a highlight of continuous indication that renewable energy strategies should be adapted.

5.2 The Outlook of Finland’s Future Climate and Energy Transition

The observation of the previous figures indicates that Finland’s temperatures are increasing, albeit at a gradual rate. Not accounting for the gas emission resulting from the Russia-Ukraine conflict, the annual increase fluctuates between 0.5 – 1 °C. Temperatures in 2021 were 2.34 °C and in 2022 they were 3.24 °C, while precipitation was 629.19 mm in 2021, and 589.04 mm in 2022. The annual mean temperature increase is about 0.12°C. This implies that Finnish renewable energy initiatives are far from leveraging the effects of climate change in Finland for their benefit for many decades (Harpold & Brooks, 2018; National Snow and Ice Center, 2024).

As part of the Nordic countries, Finland is among the last countries affected by global warming at a slower pace than the countries in the middle of the earth, due to the indirect sunlight it receives at the oblique angle. Equatorial regions transfer heat to the north with atmospheric circulation and ocean currents. Nordic countries have significantly more snow and ice compared to countries near the equator, creating an albedo effect that causes them to reflect sunlight as they melt. Arctic and Nordic countries are losing this effect as ice and snow are reduced, which are reflective rather than absorptive (Harpold & Brooks, 2018; National Snow and Ice Center, 2024).

Although Nordic countries are experiencing climate change at a slower pace than mid-latitude regions, they are warming faster (UCAR, 2024). The estimated potential of Finland to capitalize on weather effects towards hydro, solar, and wind power energy production is promising. However, it is highly improbable that Finland will achieve energy independence within the next 100 years, given the current rate of temperature increase. Therefore, Finland has to depend on fossil fuel production and energy imports from neighbouring countries.

The original data was collected with 9 years of historical data. Some weather factors show slight changes, and some show evident fluctuations. The forecasted data could show notable changes as more historical data is applied.

Each of the four weather factors is connected; one graph shows how one influences the outcome of the other positively, while the other could affect it negatively, neutralizing or balancing that factor. For example, the previous graphs show a distinct correlation between cloud cover reduction and water evaporation for higher precipitation levels. Cloud cover, precipitation, air temperature, and wind speed exhibit varying trends.

Anecdotal evidence suggests Finland's extreme cold weather is becoming more pleasing for renewable energy production, and mid-summers are seeing more areas where production can be utilized for better solar and hydro reservoirs. Cloudy winters with low solar radiation availability would impact energy demand on sudden climate events of cold days, such as heating and lighting, leading to over-reliance on stored energy or backup systems.

Finland faces forecast fluctuation or weather variability, needing a diversified, robust energy storage system to mix the strengths and weaknesses of each atmospheric condition to manage supply-demand mismatches. A factor contributing to the increase in cloud cover can be explained by the solar radiation causing warmer surface temperatures in cold regions like Finland. The warming contributes to the melting of snow and ice, which would influence humidity levels. This leads to cloud formation when warm air rises, cools, and condenses. Solar radiation heats the surface, driving an upward current, enhancing cloud development (Dima & Voiculescu, 2015; Harpold & Brooks, 2018; National Center for Atmospheric Research, 2019).

Overall, forecasted cloud cover suggests manageable impacts on Finland’s renewable energy potential with moderate climate changes, indicating the continued strategy of using stored energy from the summer to the winter season, investments towards more solar panels, hydro generation infrastructures, and advanced wind turbines adapting to higher wind speeds. As atmospheric conditions gradually improve and align with Finland's sustainable energy objectives, they lead to a positive outlook for the country’s renewable energy goals. Wind and solar have the potential to contribute to the energy mix; when needed, hydropower will support them, reducing the need for prolonged reliance on fossil fuels.

Forecasts conclude that Finland should not rely on fossil fuels for years to come and start investing now in advanced battery energy storage technologies, grid management systems, and integrated water management strategies to improve water quality, reduce flood risks, and support biodiversity—balance water use among agriculture, industry, and ecosystem.

6 Discussion and conclusion

This chapter outlines the key empirical results and conclusions of the study. The observations in this study serve as a testament to the potential of machine learning in weather prediction. The study provides a comprehensive overview of the current capabilities and future potential of smart energy use in enhancing quality of life. Finally, the direction for future studies is presented, and the chapter concludes with the suggested solutions for the Finnish industry in response to global warming.

6.1 Challenges and predictions

The world has entered a new age characterized by the innovation brought by big data. Weather impacts everyone, and accurate weather data forecasts are needed to optimize the use of power plants. Weather predictions of clouds and precipitation could have numerous positive impacts on society, as many aspects depend on good weather predictions. A snowstorm is a wind that is too strong, having variables that can disrupt operations if not mitigated without proper measures.

Finland's future goal is to enable everyone and every business to take full advantage of weather data and explore innovative ways to benefit from it. Climate change impacts the efficiency of various industries, with the energy sector being particularly dependent on weather conditions. Electric vehicles, more solar panels, and offshore wind turbines are being integrated into Finnish society yearly, necessitating Finland’s significant investment in energy solutions.
Finland has two choices:

1. Continuing its current path, which may require purchasing additional energy, to a greater extent than typically observed due to demand moving towards smarter cities and options.
2. Adapt by embracing climate change and utilizing its potential to reach higher energy production.

If Finland chooses the first option, it likely leads to increased debt, while the latter option promotes economic growth. The second option potentially would position Finland as one of the leaders in Europe in energy export, reinforcing dependence on Finnish energy resources among other nations in the forthcoming decades. To achieve this, Finland needs considerable investments in battery energy storage systems (BESS) to meet the demands of new renewable energy infrastructure installation and electric vehicles (EVs).

The transition from traditional to AI forecasting has enhanced how we look at prediction accuracy and adapt to certain statistics for short-term weather events that would be critical in optimizing solutions for disruptions. Renewable energy sources are heavily influenced and depend on strong weather conditions. Integrating energy systems combined with storage technologies and demand response mechanisms maintains production efficiency significantly on good versus bad weather days or fluctuating weather patterns.

Some renewable power plants require more operation costs and increase energy demand due to extreme weather events such as heat waves decreasing power plant efficiency as storms disrupt supply chains and transmission lines. The solution forward is to build robust renewable infrastructures. With this, Finland can benefit from the evolving electricity market, expanding BESS to enhance renewable energy trading and balancing supply and demand.

6.2 Limitations

As the role of integrated energy systems links production and consumption, connecting different infrastructures from different sectors, from industries to transportation to the power grid, it will optimize costs and emissions by flexible use of renewable energy. Machine learning methods like time-series analysis combined with ARIMA or SARIMA are the best options for adopting forecasting towards clear weather as data is analyzed in a slower, thus more accurate manner. This was proven when comparing Gradient boosting models like LightBGM to XGBoost. During this thesis, Gradient boosting models have proven superior to both ARIMA and SARIMA in non-stationary short historical data weather analysis.

While this study focused on time series predictions, its approach was based on historical weather observations from a single location, Vaasa, Finland. Weather predictions require vast data of spatio-temporal observations from multiple locations. Even then, they can only predict the weather for a very short time in the future. However, the new models don't rely solely on historical trends. The traditional weather prediction systems, such as Numerical Weather Prediction (NWP) models and hybrid ML models, utilize dense spatio-temporal data from large sensor networks like satellite imagery, ground sensors, and atmospheric reanalysis datasets like ECMWF ERA5 to simulate the physical dynamics of the atmosphere. Therefore, the applicability of the models is limited and unable to capture complex spatial interactions, capturing only local trends rather than full-scale weather dynamics or frontal movements that drive much of the weather variability.

The main dilemma in forecasting weather and energy consumption lies in the underlying non-stationary nature of time series data. Stochastic models that capture seasonal effects, such as colder winters or wetter autumns, only work if the system stays stationary. Non-stationary means that the mean, variance, and seasonal patterns change over a period, making them often unpredictable. Therefore, purely stochastic models can't account for these as they rely on the assumption that past patterns repeat. Long-term climate change, like global warming, may show persistent trends. Therefore, they can be captured through simple statistical analysis rather than complex ML Models. Machine learning models, particularly those relying on historical data trends, assume some level of stationarity to make accurate predictions. Non-stationary data may capture irrelevant patterns for future periods, degrading performance over the long-term. This is critical in climate change, where environmental structures undergo shifts without incorporating external driving variables.

The models used for Figures 28, 30, 31, and 32 contain very long-term forecasts extending ten years into the future. These projections are not validated in benchmarked backtesting, such as predicting known past values from actual observations. Therefore, projections do not assess the true accuracy or effectiveness of the models. The purpose of models was to introduce historical data for training and evaluate various metrics for model testing. Although performance metrics such as R^2 and RMSE are introduced, they become meaningful when calculated on withheld test data. The ML models can be prone to overfitting the training data if not properly regularized; otherwise, the accuracy of the models is not verifiable. The risk of overfitting emphasizes the importance of using separate training data for the models, as it occurs when the model captures incidental fluctuations instead of underlying signals—particularly when trained on small or noisy datasets. A more effective approach would be to compare data from the previous year in training-validation-test splits. This way, it would not limit the interpretability of R^2 and RMSE. Despite the limitations in forecasting long-term or irregular weather patterns, these models demonstrate the potential in capturing the seasonal trend cycles, from peaks of winter to summer temperature plateaus, highlighting their value in short-term or trend-based forecasting applications.

6.3 Suggestions for future research and solutions

Finland is exploring the development of a domestic hydrogen value chain, with research indicating a potential hydrogen economy. This is an interesting future that needs to be further studied. Developing new technologies for the future is crucial. Finland's vision is to become zero fossil fuel users and produce a lot of hydrogen to export to other countries. Increasing exports of goods generate more income, reducing the need for loans and boosting the Finnish economy.

Electricity prices depend on the time people charge their utilities, such as EVs. Progress towards energy independence would ensure that Finland would have abundant energy so that citizens would not need to depend on what time of the day they would charge, as it would lead to prices being naturally lowered due to having so much energy to spare.

Finland aims to be the first welfare society with net-zero emissions by 2035. The means to achieve this include government support for the transition to zero-emission heating; shifting the focus of taxation to environmental harm; gradually phasing out fossil fuels; implementing nearly-emissions-free electricity and heat production by the end of 2030; developing low-emissions transport systems; reducing the carbon footprint of construction; and improving the energy efficiency of existing buildings.

New emerging technologies such as electrification and system integration, hydrogen and electric fuels, offshore wind power, and BESS are the keys to Finland's carbon goals. Increased climate change unlocks these technologies' full potential to a net zero society. With a global uranium consumption rate of approximately 68,000 (tU) per year and current worldwide reactors combined and demand, nuclear energy production will not be a reliable source. "Over the years 1980 to 2008, the electricity generated by nuclear power increased 3.6-fold while uranium used increased by a factor of only 2.5." Nuclear is the biggest energy producer in Finland, as nuclear power plant generation is limited, being the cleanest gas emissive non-renewable, with the current consumption rate Finland must achieve its renewable energy goals within the next 80-90 years as the world is estimated to run out of uranium by then (World Nuclear Association, 2024).

The real question is determining the threshold at which climate change becomes detrimental. The research in this thesis indicates that Finland will have sufficient energy to combat extreme weather conditions if it were to happen. The solution to climate change is not pressing the brakes on the economy; the secret lies in the opportunity to use the weather events to our benefit with more powerful measures that can only be achieved with funding and the advancement of technology. Therefore, high energy production due to climate change in Finland is the solution, making climate change a positive outlook. Melting ice, temperature rise, sea-level rise, faster wind speeds, shorter and warmer winters and heavier rains in the summers in Finland don't contradict that climate is changing, the problem resides in how fast it accumulates over the years. The study shows in this paper though Finland is going through changes; Finland is likely far from capable of utilizing the changes for its benefit in renewable energy production.

Finland will likely see changes to agriculture and the ecosystem, pursuing adaptation practices to the changing climate to sustain food production and biodiversity. The outcome will be compromised without irrigation systems that preserve crops and natural habitats through wetland conservation and drought resistance solutions. It is important for efficient water use, adaptation to short and long growth cycles, and tolerance to soil salinity. Planting trees (Reforestation) could increase forests, enhancing security and quality of life in Finland from unpredictable climate changes.

Gradient boosting provides a forecasted ‘‘medium’’ idea of warnings about weather events and changes in ecosystem health, however, the predictions cannot be relied upon, as technology is yet unable to forecast events many years into the future. With the continuous unpredictable climate change, Finland's future will still transition to a renewable energy goal of zero-emission, but not before 2035. During this progress, Finland has been a driving force in achieving economic growth creating jobs in the green energy sector and transportation networks —impacting domestic manufacturing and research to utilize resources to combat strong climates towards renewable energy generation facilities. Finland has an opportunity to leverage a potential economic boom for innovation, export solutions, and exchange knowledge between foreign countries positioning itself as a leader in the green tech industry and attracting investments.

The biggest problem today is not global warming, it is the negligence of allowing change to happen naturally corresponding to the quality of human life. This thesis argues that we shouldn't eliminate fossil fuels before 2035. This paper concludes that Finland will benefit from fossil fuels to transform its climate to a point where it enhances natural changes in wind, solar, air temperature, and hydropower, abolishing the need for emissive sources. As initiatives developed under government policies and regulations aim to steadily reduce reliance on fossil fuels in favor of locally produced renewable energy, Finland will not only become one of the least contributing countries to climate change in international efforts but will enrich the country through the involvement of communities and public collaboration, ultimately achieving energy independence and public debt freedom.

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