Aalto University
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Low Carbon Roadmap
Finnish Energy

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Executive summary

This report, commissioned by Finnish Energy, endeavors to chart a course for Finland's energy future, specifically focusing on power and heat production. The objective is to craft a comprehensive roadmap for the years 2035 and 2050. The study explores three distinct scenarios - "Slow", "Assumed", and "Ambitious" progressions - each grounded in meticulous research, data analysis, and collaboration with industry experts.
In line with Finnish Energy's directive, the report critically assesses and updates assumptions from the previous roadmap, drawing comparisons with some European counterparts (Belgium, France, Germany, and Italy) to glean insights for Finland's unique energy transition.

After analysing the previous roadmap 2019 from Finnish Energy and the current situation (2022) in Finland regarding power and heat productions, the other European roadmaps have been studied.
Those analysis showed still a strong reliance on fossil fuels in Finland, especially for the heat sector where 34% of fossil fuels are currently used. Other European countries, as they currently rely even more on fossil fuels than Finland, face the same challenge of getting rid of fossil fuels and the common strategy throughout Europe to phase-out from them is a strong electrification of the industry. This will be possible with an increased installation of renewable energy sources such as wind and solar. Finland, like France, will also continue to rely on nuclear power production.

Four assumptions were considered in this 2023 forward-looking low-carbon roadmap for 2035 and 2050: interest rates, carbon prices, climate change effects, and technology developments. The three scenarios were obtained based on variations of these assumptions.
The "Slow" scenario is the only one that reaches carbon neutrality in 2040 (by adding carbon sinks). This scenario considers the least favorable assumptions such as high interest rates, low carbon prices, huge impacts of climate change on the biomass growth and hydro production and low technology developments. The "Assumed" and "Ambitious" scenarios both reach carbon neutrality in 2035 (by adding carbon sinks). While the "Assumed" scenario seems the most realistic of both given the current information available, the "Ambitious" scenario considers the most favorable assumptions for the low carbon transition in Finland.

Overall, for power, findings suggest that solar production could increase up to 50 times compared to 2022, with wind power emerging as the predominant source, especially through offshore wind farms after 2035. Nuclear production ties closely to combined heat and power SMRs, dependent on the scenario, leading to an overall increase in power production ranging from 73% to 241% compared to 2022. Fossil fuels are phased out entirely, power imports reduced, and the hydrogen economy correlates closely with wind power developments. Furthermore, biofuels usage is significantly decreased by 2050.
For heat, a reduction in forest fuels is achievable, while waste heat experiences substantial increases across all scenarios. Electrification leads to up to 26 times higher heat production compared to 2022, with other changes including a rapid decline in fossil fuels, a slight overall decrease in heat demand, and the presence of SMRs favouring heat production.

Regarding the CO_2 emissions, all scenarios in 2050 foresee direct emissions solely from heat and power resulting from waste incineration. The magnitude of these emissions varies, contingent on recycling efforts and efficiency, including the overall assumption for waste production.
In the "Ambitious" scenario, there is potential for a remarkable 78% reduction in remaining emissions compared to 2022. As wind power and the hydrogen economy mutually thrive, forest fuels are anticipated to gradually yield to waste heat, electrification, and SMRs.

Finally, it is crucial to emphasise that the outcomes of each scenario's low-carbon roadmap strictly correlate on the variability of identified general assumptions. While the effects on each energy source have been meticulously studied, uncertainties stemming from unforeseeable events and developmental factors up to the year 2050 are evident in several instances, resulting in substantial deviations between scenario outcomes.
Despite these uncertainties, the significance of this report for Finland's low-carbon roadmap in 2023 lies in its role in steering decisions towards a low-carbon future, encompassing both electricity and heat production. A final recommendation underscores the importance of regularly updating the roadmap every two to three years, relying on empirical reassessment of assumptions for each scenario.

1 Introduction

Against the backdrop of Finland's ambitious carbon neutrality goals, this report presents a strategic vision for Finland's low-carbon future in power and heat production by 2035 and 2050. The study builds on Finland's impressive progress, evidenced by a remarkable increase in clean energy production, reaching almost 90% emission-free electricity in 2022.[1] [2] This positive trajectory positions Finland favorably to achieve its carbon neutrality goal by 2035.

The Finnish industry showcases a significant commitment to electrification, reducing fossil fuel usage, and boosting renewable energy, particularly in nuclear and wind sectors. These achievements form a solid foundation for the ambitious "Roadmap 2035 and 2050", aiming to reduce greenhouse gas emissions and foster a resilient economy.

The methodology and analysis scope of this report include three scenarios for 2050 – "Slow", "Assumed", and "Ambitious" progressions – focusing on key assumptions like investment environment, carbon prices, climate change impacts, and technology developments.
Comparisons with the previous 2019 roadmap highlight revisions, anticipating increased electricity consumption to 111 TWh by 2035, reduced fossil fuel usage in electrified industry, and decreased urban heating production to 35 TWh by 2050. Along with that, the comparative study with European countries offers insights into diverse decarbonization strategies.

This report identifies "Updated assumptions" of the Finnish roadmap 2023, forecasting decreased interest rates, rising carbon prices, and considering impacts of climate change and technology advancements. Perspectives on small modular reactors, offshore wind, and hydrogen production guide the transition to a zero-emission energy system.
The three progression scenarios provide concrete pathways inspired by recent renewable energy achievements. This report is a crucial tool for planning Finland's low-carbon future. Its relevance lies in the solid foundation of Finnish progress, aiming to guide decisions in climate policy and emphasizing a holistic approach to electricity and heat production transition.

2 Methodology and demarcations of the analysis

In this chapter, the comprehensive approach undertaken to update the Finnish roadmap will be explored. The methodology, a key component of this process, outlines the strategies employed to achieve the results. Simultaneously, the demarcations serve as guideposts, ensuring focus aligns with the chosen path and preventing unnecessary excursions, thereby maintaining the report's accessibility.

Collaboratively agreed upon with Finnish Energy, the approach involves crafting three scenarios each for district heat production and power production in Finland by the year 2050. These scenarios— "Slow", "Assumed" and "Ambitious" scenarios—provide a nuanced perspective for future planning.
Built upon power or heat source-specific assumptions with numerical values, these scenarios reflect the deviation or alignment with the Finnish roadmap from 2019. Cumulatively, an estimate for the total power or heat production in the updated Finnish roadmap for 2050 is offered by them.

To formulate assumptions for each energy source, the focus is on identifying realistic and comprehensive general assumptions. These assumptions need to be independent of each other, easy to comprehend, and applicable across the board. Consequently, the updated Finnish roadmap's general assumptions are categorized under four pillars: investment environment, carbon prices, climate change impacts, and technology developments.

Within the investment environment, it becomes evident that low interest rates would drive investments in renewable energy technologies, whereas high interest rates would hinder enhanced investment programs. Accordingly, high interest rates are incorporated into the "Slow" scenario, moderate interest rates are adopted by the "Assumed" scenario, and low interest rates are relied upon by the "Ambitious" scenario.
In terms of carbon prices, dictated by the Emission Trading System (ETS), high prices incentivize investments in renewable energy, while low prices disadvantage the energy transition. As such, low carbon prices are considered by the "Slow" progression scenario, moderate carbon prices are integrated into the "Assumed" scenario, and high carbon prices are relied upon by the "Ambitious" scenario.
Considering the impacts of climate change, ranging from extreme weather events to average yearly temperature increases, milder climate change impacts are deemed a "best case scenario" for the "Ambitious" scenario. Meanwhile, moderate climate change impacts are anticipated by the "Assumed" scenario, and aggravated climate change impacts are considered by the "Slow" progression scenario.
As the final general assumption, it is recognized that technological advancements significantly impact the effectiveness of carbon-neutral energy sources. Accordingly, a favorable technology development environment characterizes the "Ambitious" scenario, while moderate and weak environments are contended with by the "Assumed" and "Slow" progression scenarios, respectively.

In conclusion, an analytical method was chosen for updating the Finnish Roadmap, avoiding complex modeling programs. This decision aligns with the goal of presenting a report that is both comprehensible and manageable for a wider audience.

3 Assumptions and outcomes of the Finnish roadmap from 2019 and historical data from 2022

The situation in Finland in 2022 regarding power and heat production is depicted in Figure 1. The previous version of low carbon roadmap for Finland was made in 2019. After that, there has been major changes in world politics and economy. Due to this, in 2023 it is possible to use only some of the assumptions made in 2019.

In the 2019 low carbon scenario the total electricity consumption was estimated to increase to 111 TWh by 2035 and to 135 TWh by 2050.[3] For comparison the electricity consumption of Finland was 82 TWh in 2022.[4] The estimated increase is due to strong electrification of industry. On other sectors, electricity consumption is also assumed to increase, but the increase is not that significant. In the 2023 low carbon roadmap, the electricity consumption can be assumed to increase as well, but the amount of increase had to be reevaluated in comparison to the previous roadmap.

Because all sectors aims to reduce emissions, industry will use more electricity in order to phase out from fossil fuels. Nuclear energy plays a significant role in electricity production, the previous roadmap assumed that Olkiluoto 3 and Hanhikivi 1 nuclear reactors would produce electricity by 2035. Also, that wind power production would increase to 30 TWh by 2035 and 47 TWh by 2050.[3]

In district heating, the portion of fossil fuels was predicted to decrease and waste heat portion to increase. Overall district heating production was estimated to decrease from 38 TWh to 35 TWh by 2050.[3] District heating section was still heavily depending on forest fuels in this 2019 roadmap. At the same time the goal is that nothing is burned. Small modular reactors (SMRs) were considered as a possibility, but they were not seen as a technology mature enough to produce heat. SMRs have developed faster than expected and, therefore, could act as a possible solution to reduce the use of forest fuels.

All potential hydro power is already harvested in Finland and in the future, only minor changes can be expected. The current conventional nuclear power plants were assumed to continue operation at least until 2050 and Hanhikivi nuclear power plant was assumed to be completed. Now it is already known that all of the five current reactors have a licence to operate at least until 2050 and Hanhikivi nuclear power plant will not be completed. SMRs were not considered to produce electricity but, as the technology has developed faster than expected, they can be taken in consideration also in power sector in the 2023 roadmap.

Overall the previous roadmap is rather accurate but some elements are outdated. The big picture is kept the same: strong electrification and phase-out from fossil fuels. The Figure 1 presents Finland's electricity and heat production in 2022.

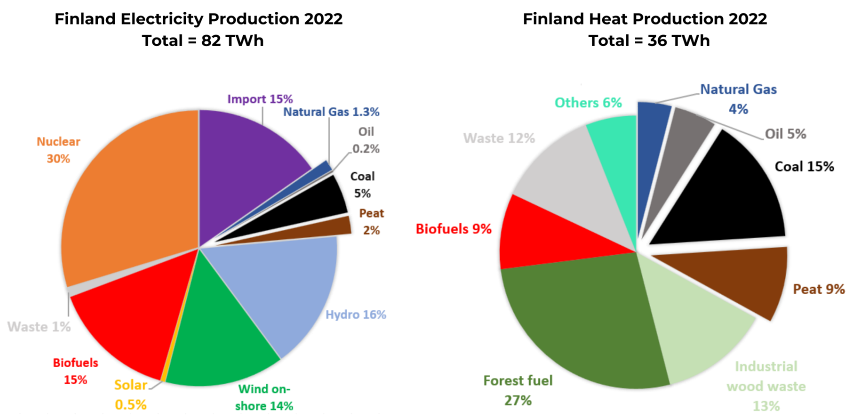

Figure 1: Finland power and heat production 2022.[4]

4 Assumptions and outcomes of the latest roadmaps of other selected countries

In this chapter, the climate goals and energy transition strategies of four European countries: Belgium, France, Germany, and Italy are examined. The focus on their roadmaps is made on how to achieve a sustainable energy future, including: an analysis of the gross shares of energy sources in power and heat generation in 2021, projected shares for achieving net-zero carbon emissions by 2050, and the identified challenges on the path to a greener energy landscape.

An overview and comparison of assumptions regarding the proportional distribution of energy sources made by these countries is provided. These assumptions play a critical role in determining the success of their energy transition efforts.
Additionally, similarities and differences between the assumptions of these countries and those in the Finnish Roadmap from 2019 are identified. This comparative analysis aims to offer insights into energy transition strategies and shared challenges, potentially supporting the update of assumptions for the Finnish roadmap in 2023.

4.1 Belgium

Overview of climate goals

Belgium has the objective to be carbon neutral by 2050. This strategy has an intermediate milestone to reduce about 55% of its emissions compared to 1990 in 2030. To do so, the Belgian strategy is based on renewable sources of energy: solar, wind power (onshore and off shore) and deep geothermal coming both from proprietary power sources and international ones. However, some sectors such as the industry cannot reach neutrality. Their emissions will be compensated by carbon removal technologies, mainly thanks to bioenergy with carbon capture and sequestration (BECCS). Belgium's gross energy sources in power and heat production for 2021 and 2050 are depicted in Figures: 2, 3.

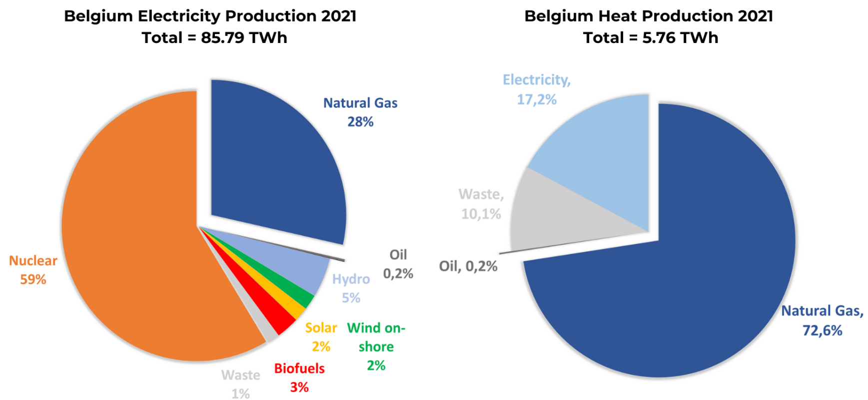

Figure 2: Belgium's gross energy sources in power and heat production for 2021.[5]

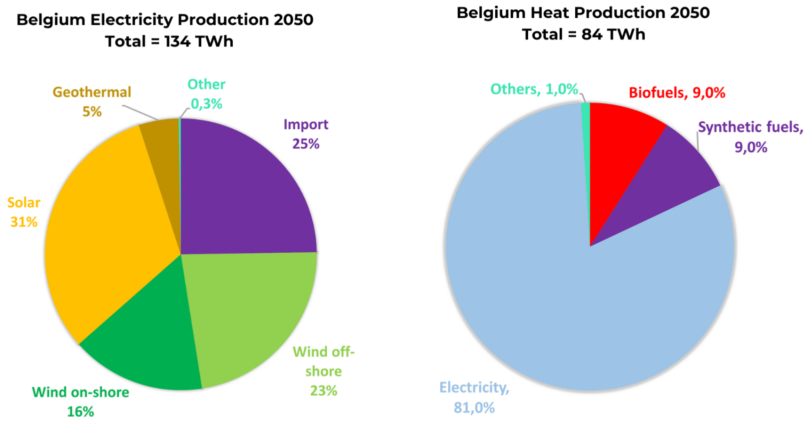

Figure 3: Belgium's gross energy sources in power and heat production for 2050.[6]

Challenges

There are several challenges that were identified to reach carbon neutrality in 2050 for Belgium. The main ones are the huge quantity of importation of electricity Belgium will have to do to reach its emission goals. To remediate to this challenge, Belgium is investing on building strong infrastructures and cooperation with its neighbouring countries.

Another key challenge will be to have enough controllable capacity to have enough power capacity for long periods (weeks) of low electricity production from both solar and wind powers. The daily flexibility can be solved with the help of the final applications (heat pumps, cars or battery storage) but longer periods of intermittence require other solutions.

4.2 France

Overview of climate goals

According to the SNBC (National Low Carbon Strategy) France has set its carbon neutrality target for 2050 and is expected to achieve complete decarbonisation of the energy sector at the same time. They plan to shift out of coal production starting in 2022. The strategy also plan a 33% reduction of the carbon emissions by 2030 compared to 2015, which corresponds to 40% compared to 1997.[7]

In order to achieve that, emissions reduction targets were set for every sectors as well as more general targets for the country itself. The long term scenario only take into account the current existing measures but short terms scenarios, for the next 5 years, have additional measures that shows better results in term of emission reduction.[8]

In 2021, France mainly relied on nuclear energy which helped the decarbonisation of the sector as more than 80% of the energy production comes from low-carbon energies. However, France still uses coal, oil and natural gas in the energy sector but also in district heating as it accounts for about 45% of the production. France's gross energy sources in power and heat production for 2021 are depicted in Figure 4.

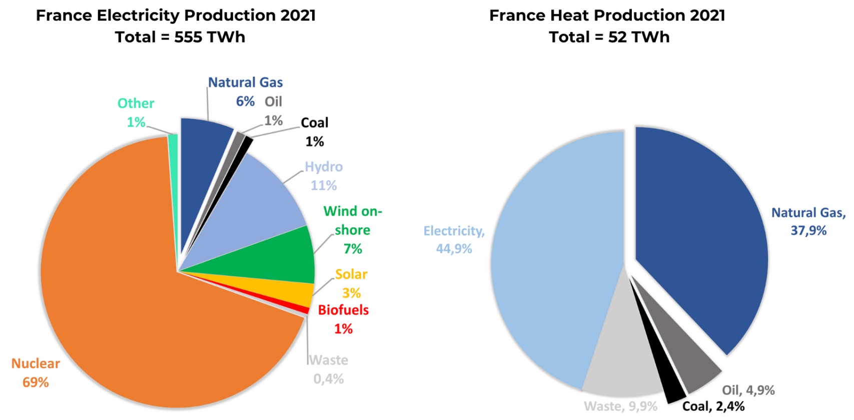

Figure 4: France's gross energy sources in power and heat production for 2021.[5]

The goal in 2050 (Figure 5) is to reduce the share of nuclear to 39% and fossil fuel to around 5% in the electricity production. To compensate this reduction, France plans on heavily investing in wind and solar power, resulting in an increase in wind power and solar power of almost 20% and 15%, respectively. As for district heating, France plans to phase out of coal and oil and drastically reduce the use of electricity by increasing the use of biomass.
Furthermore, France wants to develop SMRs with the NUWARD project launched by EDF, this project would produce 2x170 MW of electrical power and 2x540MW of thermal power. [9]

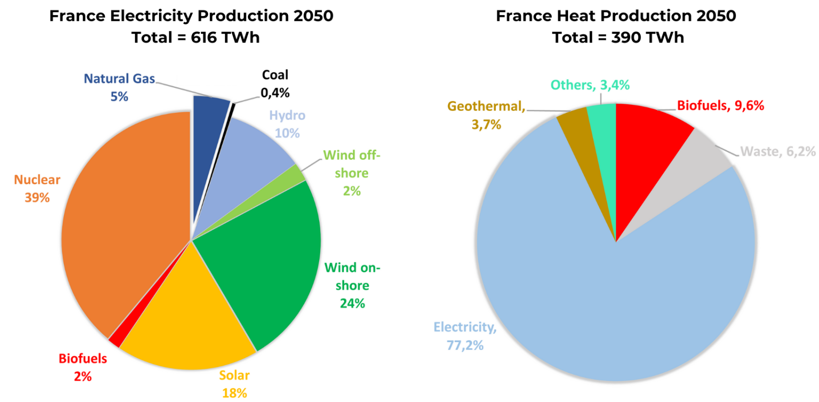

Figure 5: France's gross energy sources in power and heat production for 2050. [7][8][10]

Challenges

Several challenges were identified for France, for the building sector, it is important to accelerate the renovation of buildings that consume too much energy as 70% of the 2050 building stock could consist of building built before 2012. To achieve that, yearly investments will be needed.
In the energy sector, a major challenge will be to increase the energy efficiency and the consumer energy sobriety, to do so, it will be important to lower the energy intensity of the french economy through measures and to adopt the most suitable and efficient technologies in all sectors. The scarcity of rare metal resources needed for renewable energy technologies is also an issue that needs to be considered for the future.
Another challenge will be to ensure that Overseas France will get an equal access to electricity compared to Metropolitan France.

4.3 Germany

Overview of climate goals

Germany's climate goals include achieving greenhouse gas neutrality by 2045, raising the 2030 emissions reduction target to at least 65% compared to 1990 levels. Germany also aims to reduce emissions by at least 88% by 2040, emphasizing the role of natural ecosystems as carbon sinks. The focus is on reducing future emissions across all sectors to make Germany more climate-resilient and to meet its ambitious climate targets. Although sectors like power and district heat share common dependencies, the current status and the continuous journey towards decarbonisation varies significantly.[11] Germany's gross energy sources in power and heat production for 2021 are depicted in Figure 6.

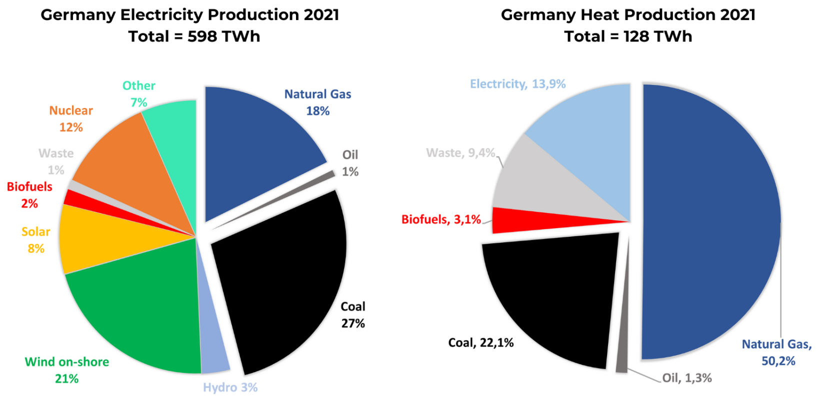

Figure 6: Germany's gross energy sources in power and heat production for 2021.[5]

In 2021, fossil fuels played a dominant role in both the power production and heat generation sectors. Coal stood out as the primary energy source for electricity production, accounting for the largest share, while renewable energy sources contributed to 41,4% of the overall electricity mix. Regarding the district heat production, natural gas took the lead, supplying approximately half of the energy needs in 2021, whereas renewable energy sources had a smaller presence in this sector, comprising only 17% of the total energy mix. Germany's gross energy sources in power and heat production for 2050 are depicted in Figure 7.

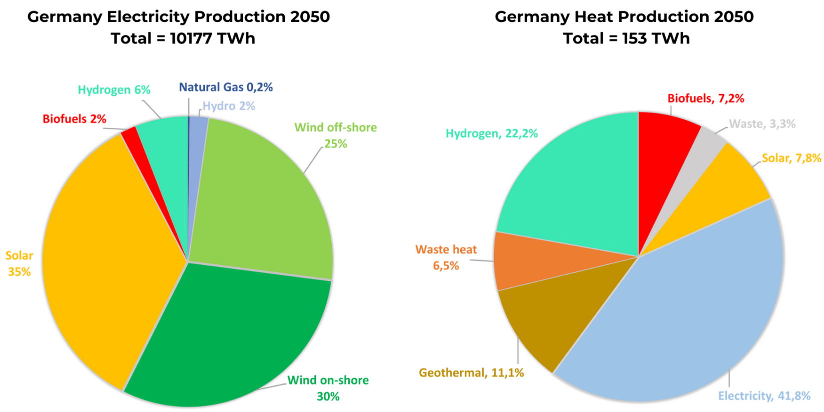

Figure 7: Germany's gross energy sources in power and heat production for net zero 2050.[12]

By 2050, the power sector will be exclusively powered by renewable energy sources with wind and solar energy playing a dominant role, contributing to over 90% of the electricity mix. Wind energy is set to triple its share compared to 2021, while solar power will witness an astonishing increase, growing by a factor of over 4.

In terms of district heat production, heat pumps will emerge as the primary source, rising from its previous third position in 2021 to claim a share of approximately one third.

Furthermore, hydrogen, which was yet absent in 2021, will play a substantial role in the fossil fuel-free district heat sector of 2050, contributing to over 20% of the overall heat generation mix.

Challenges

The transformation towards a net-zero energy sector by latest 2050 does not come without major challenges. For instance, Germany is investing in expanding wind power capacities to boost renewable energy in its electricity mix. However, the distribution of wind power capacity (mainly in the North) and industrial centers (mainly in the South) necessitates substantial upgrades in the power infrastructure, including high-capacity transmission lines. These lines are not only difficult to implement in a densely populated country like Germany, but also come with great resistance from the population in affected areas. Although coming with higher costs, underground transmission cables could be a solution to overcome these potentially time-consuming challenges in those areas with the greatest opposition.

In addition, the promotion of electric vehicles (EV) is a priority, backed by incentives like tax benefits and purchase premiums. While charging infrastructure is expanding, high electricity prices pose a challenge to EV adoption, requiring a focus on increasing renewable energy generation, storage, and efficient power infrastructure.

Furthermore, phasing out coal power may encounter public resistance, necessitating government support for affected regions, including economic transformation and job preservation. Finally, Germany is also investing in clean technologies, especially hydrogen, as a mid-term energy source to replace natural gas. However, transitioning from natural gas to hydrogen involves significant infrastructure modifications to ensure safety.

Last but certainly not least, heat pumps, leading the way in the heat sector, currently face challenges due to high electricity prices and the substantial replacement costs associated with older buildings that still rely on fossil fuels for heating. These older structures are in need of renovation. Given that the financial burden may prove difficult for the general population to bear, it becomes vital for the government to introduce subsidies or other programs aimed at making the adoption of heat pumps not only more appealing but also technically feasible.

4.4 Italy

Overview of climate goals

Italy has significantly transformed its energy system since 2010, favoring natural gas and renewable sources while reducing coal and oil use. This shift resulted in a 15% drop in energy intensity (the ratio of total final consumption to GDP) from 2005 to 2021.

Italy is progressing towards its 2030 emissions reduction and energy efficiency targets as outlined in the National Energy and Climate Plan (NECP). Yet, further substantial efforts are required to meet more ambitious 2030 goals within the European Union's "Fit-for-55" package and "REPowerEU" plans [13], which aim to reduce reliance on Russian fossil fuels.

Between 2005 and 2019, Italy cut greenhouse gas emissions by almost 30%, with a dip in 2020 due to the COVID-19 pandemic. Preliminary data indicates a 4% emissions reduction in 2021 compared to 2019. Italy is committed to achieving carbon neutrality by 2050.[14] Italy's gross energy sources in power and heat production for 2021 are depicted in Figure 8.

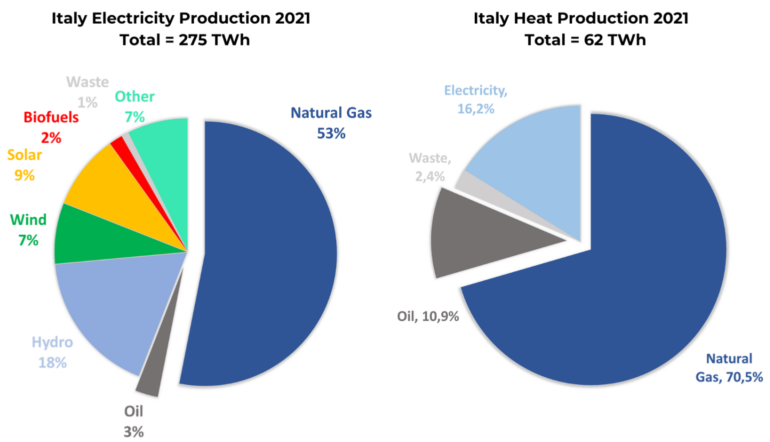

Figure 8: Italy's gross energy sources in power and heat production for 2021.[5]

In 2021, Italy diversified its energy production, with a growing focus on renewable sources. Natural gas accounted for 53% of electricity production, followed by hydroelectric (18%), solar (9%), wind (7%), and other renewable sources (7%). Fossil fuels, such as oil, had a limited share (3%). Overall, Italy produced 275 TWh of electricity.

In the heating sector, natural gas dominated at 70,5%, followed by heat pumps (16,2%), while oil represented 10,9% of thermal production. These data reflect a growing commitment to more sustainable energy sources and energy efficiency in Italy. Italy's gross energy sources in power and heat production for 2050 are depicted in Figure 9.

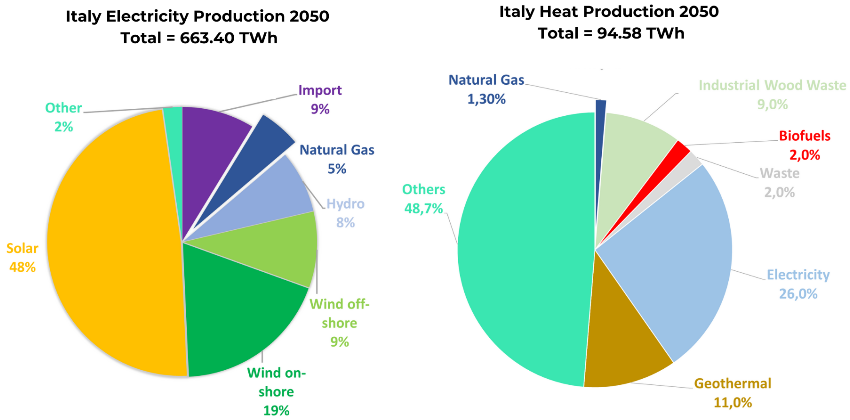

Figure 9: Italy's gross energy sources in power and heat production for 2050.[15] [16]

In 2050, Italy will witness a significant transformation of its energy landscape, with a greatly improved electricity production compared to 2021. Solar energy will be the dominant source, accounting for 48% of the total production. Onshore and offshore wind energy will gain further prominence, contributing 19% and 9% of electricity production, respectively. Imports and exports will continue to play a significant role at 9%, while hydro energy will account for 8% of production, and natural gas will be responsible for 5%. Other sources of energy, such as geothermal, waste, etc., will make up 2%. Overall, Italy will produce 663,40 TWh of electricity in 2050.

In the heating sector, 2050 will see a significant diversification with a growing emphasis on energy efficiency. Heat pumps will become more important, contributing to 23% of thermal production. Combined heat and power (CHP) plants will represent 44%. Other sources of thermal energy, like geothermal, solar thermal, biofuels, and industrial waste heat, will play a key role in thermal production. The use of hydrogen will remain marginal. Overall, Italy will produce 94,58 TWh of heat in 2050.

These data will reflect a significant progress for Italy towards a cleaner energy production, with a growing emphasis on renewable sources for both electricity and heating. The reduction in gas usage and the increase in solar and wind energy will mirror a substantial transition toward greater energy sustainability by 2050, in line with the emission reduction and energy efficiency goals set by the Italian National Energy and Climate Plan (NECP) and European policies.

Challenges

To reach this goal, Italy's Long-Term Strategy (LTS) includes an 84-87% reduction in greenhouse gas emissions, a substantial increase in renewable energy production, widespread electrification across sectors, sector coupling, and flexibility solutions. Additionally, it involves transitioning from natural gas to hydrogen and synthetic fuels, promoting public/shared transportation over private cars, and accelerating building energy renovations.

4.5 Summary and overview of assumptions

The charts below (Figures 10 and 11) summarize the proportions in energy sources for electricity and heat in 2021 and projected for 2050 presented above.

Electricity production

Examining the situation in 2021 (excluding imports), the data reveals a significant reliance on fossil fuels, with natural gas dominating in Belgium (28,6%), France (6,4%), Germany (17,7%), and Italy (53,1%). The high percentage of nuclear energy in France (68,4%) underscores a strong dependency on this source in the country, and Belgium also relies predominantly on nuclear power (58,7%). However, it should be noted that Italy and Germany have already begun diversifying their energy production, with a substantial share coming from renewable sources such as onshore wind and hydro power.

Now, focusing on 2050, a pivotal year in the goal of emission reductions, significant changes emerge. In all analyzed countries, imports from other nations are now considered, unlike in 2021. The import of electricity becomes a significant component, representing over 20% in Belgium and 8,7% in Italy. This could indicate increased interconnection and collaboration between countries to achieve energy goals. A transition toward renewable sources is evident in 2050. For instance, Italy demonstrates a notable increase in renewable energy, with solar accounting for 48,5% and onshore wind at 18,8%. Germany, on the other hand, appears to focus on off-shore (24,8%) and on-shore (30,4%) wind energy, in addition to solar at 34,9%. France reduces its dependence on nuclear energy to 39%, significantly increasing the share of solar (17,9%) and wind (26,7%).

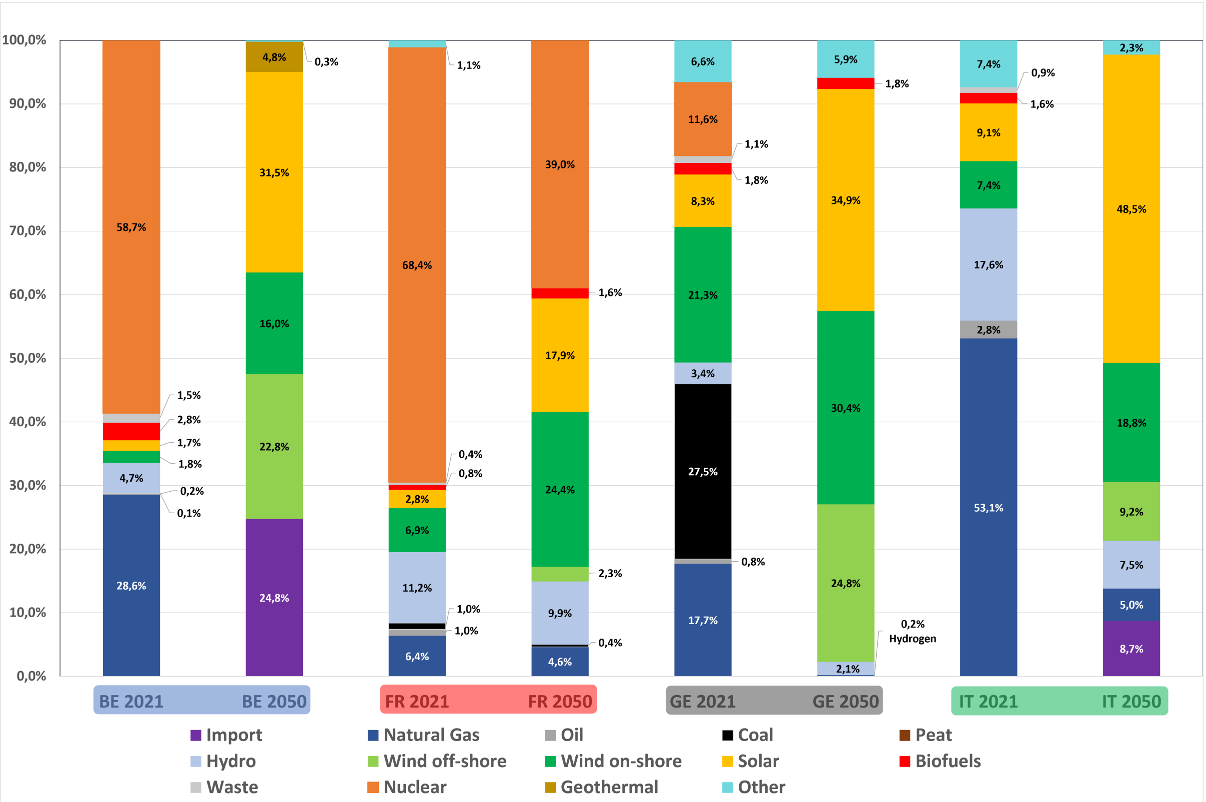

Figure 10: Summary of electricity production percentages of each country analysed for 2021 and 2030 (imports not considered in 2021).

Heat production

The chart below (Figure 11) highlights significant changes in the energy sources for heat of Belgium, France, Germany, and Italy between 2021 and 2050. In 2021, there is a strong dependence on fossil fuels, with notable percentages such as 72,6% for natural gas in Belgium. In 2050, clear signs of transition to more sustainable sources emerge, with remarkable increases in the use of electricity, reaching 81% in Belgium and 77,2% in France.

There is a notable decrease in natural gas, oil, and coal in favor of more eco-friendly sources. Biomass and industrial waste gain importance as energy sources, especially in Belgium and Italy, accounting for 9% and 9,6%, respectively, in 2050. The increase in geothermal energy in Germany in 2050 suggests a greater adoption of low-carbon technologies, reaching 11,1%.

Overall, the chart highlights a positive transition towards a more sustainable energy mix by 2050, with a significant reduction in the use of fossil fuels.

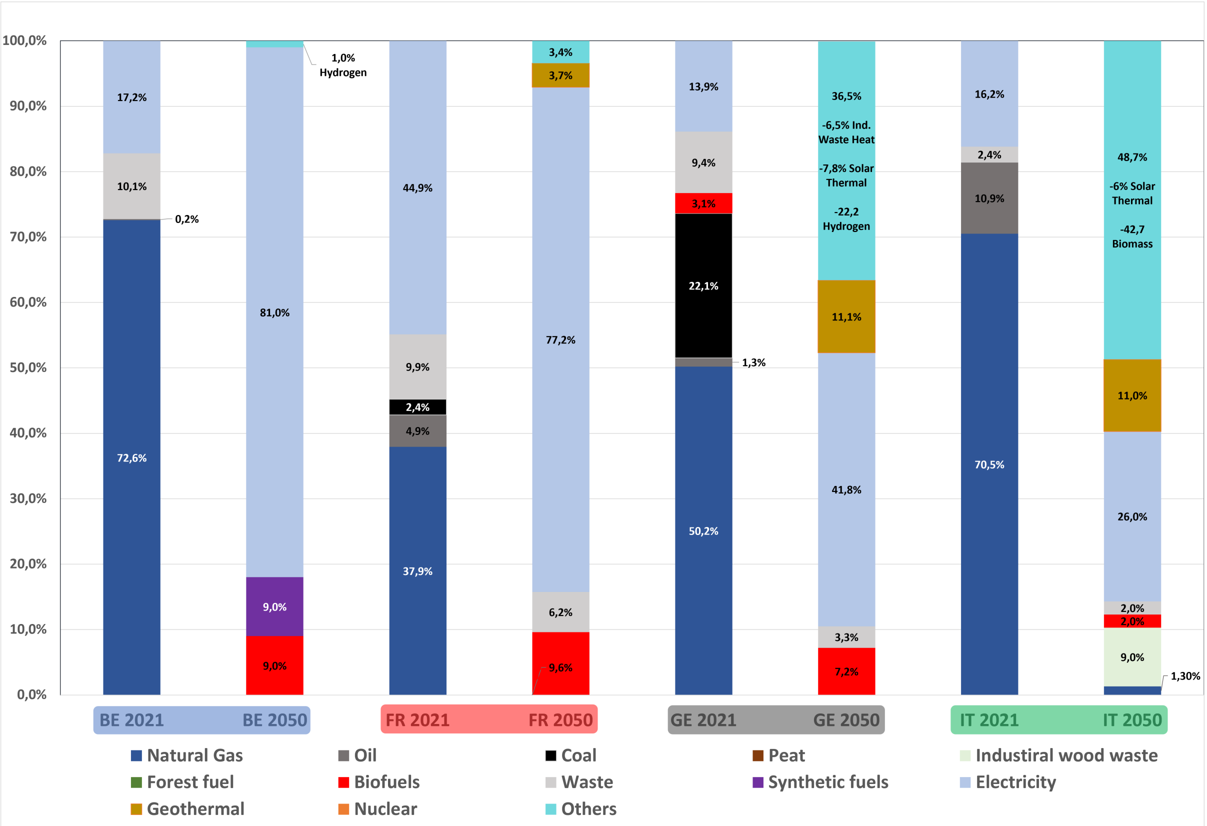

Figure 11: Summary of heat production percentages of each country analysed for 2021 and 2030 (imports not considered in 2021).

Similarities and deviations to the Finnish roadmap 2019

To begin with, every roadmap expect an increase in power production by 2050 mainly due to the strong electrification of the industry. However, while Belgium, Italy and Germany are phasing out of nuclear energy to focus more on solar and wind to meet the increase of the demand, France will still be using nuclear energy along with wind and solar like Finland. Overall, every country will be using wind and solar in their energy mix to phase out from fossil fuels and reduce the carbon emissions of every sectors but only France and Finland will continue to rely on nuclear energy.

Another similarity between France and Finland is the consideration of SMRs in their roadmap even though France is slightly more supporting the technology as a SMR project is already being backed-up by the government.[7][8][9]

Finland is aiming to reduce its heat production by 2050 as the demand is seen to decrease, but it is not the plan of the other countries as they are planning to greatly increase their heat production to meet an increasing demand by 2050. All countries are transitioning away from fossil fuels with similar plans. Belgium and Finland, excluding geothermal reliance, share the goal. Electrification in heating production facilitates the green transition, increasing electricity's role to replace coal and natural gas, with Finland having a smaller share compared to other countries.

5 Updated assumptions of the Finnish roadmap 2023

This chapter presents assumptions, that are used to create the Finnish roadmap 2023. The assumptions are divided into four different parts which are: investment environment, carbon prices, climate change impacts and technologies development.

5.1 Investment environment

The investment environment is defined by interest rates which are what a borrower is paying to get a certain amount of money from a lender, they also include a compensation consisting of a payment equal to the loss of purchasing power and a balance representing the interest of the lender. The rates does not only varies with the inflation but also depend on the amount borrowed, the period of the transaction, the purpose, government policy and other factors.[17]
Interest rates are either displayed as short-terms, usually 3 months, or long-term, usually 10 years, by using the forecast data available. The current interest rates is estimated to be around 3,5% and several analysis predict that interest rates will decrease below 3% in the next 2 years, and could even reach 1,5%. Contracts for wind power plants are long-term, thus contracts signed in those 2 years will have an impact for up to 2050.[18]

- **Low interest rates:** A low interest rate encourages company and private actors to invest in renewable energy technologies, leading to a growth in energy production in the future. Therefore, the lower the interest rates are the better it is for the green transition.
- **Moderate interest rates:** A moderate interest rate would still help supporting companies or private actors in investing in renewable energy technologies resulting in a moderate growth in renewable energy production in the future.
- **High interest rates:** A high interest rate reduces the number of investments made by companies and private actors as it is less attractive for them, resulting in a slow growth in renewable energy production in the future. Thus the higher the interest rates the worse it is for the sector.

As more and more investment are needed in the energy sector to continue the green transition, the interest rates have to be closely monitored to facilitate the investments in the sector.

5.2 Carbon prices

The price of emissions traded in the EU ETS rose from 8€ per ton of CO_2 equivalent at the beginning of 2018 to around 60€ more recently. The EU ETS involves approximately 10 000 companies in the energy and manufacturing sectors, as well as airlines operating within the European Economic Area (EEA). Around 40% of the EU's greenhouse gas emissions fall under the EU ETS.[19]
Forecasts suggest that European Union Allowances (EUAs) could average 81,27€ per ton in 2022 and 88,25€ in 2023.[20] The price of pollution in the European Union might rise to as much as 85€ per metric ton by the end of the decade, as the bloc tightens its carbon market and accelerates the transition to clean energy.

- **Low Carbon Prices:** A low carbon price might not provide sufficient incentive for companies to invest in clean technologies and reduce their emissions. This could lead to a less favorable investment environment for green technologies. However, data suggests an upward trend in carbon pricing in both the reference and more ambitious scenarios, indicating a progression beyond this scenario. It could potentially discourage businesses from adopting cleaner technologies, potentially leading to a stagnant investment climate.[21]
- **Moderate Carbon Prices:** A moderate carbon price can provide a balanced incentive for companies to invest in clean technologies without imposing an excessive burden. This could create a favorable investment environment. Data indicates a current situation within this scenario, showing a consistent increase in carbon prices. It might incentivize investments in cleaner practices, promoting innovation and growth in green sectors.[21]
- **High Carbon Prices:** A high carbon price can offer a strong incentive for companies to reduce their emissions and invest in clean technologies. However, it could also increase production costs and

have a negative impact on the profitability of businesses. Forecasts suggest a movement toward this scenario with a projected further increase in carbon prices. While promoting a reduction in carbon footprints, high prices could increase operational costs, particularly impacting carbon-intensive industries and potentially discouraging investments.[22] [23]

According to an Ernst & Young report, carbon offset prices are projected to reach $80 USD per ton of carbon dioxide by 2030 for the low scenario, $150 USD per ton by 2035 for the moderate scenario, and the same report anticipates a further increase towards the $150-200 USD range by 2050 for high prices.[24]
Concurrently, the European Union is actively engaged in a transformative journey with the European Green Deal, aimed at achieving climate neutrality by 2050. At the heart of this initiative lies the "Fit for 55" package, targeting a 55% reduction in EU greenhouse gas emissions by 2030, signifying a concrete commitment to substantial actions. To reach these objectives, the EU is extensively overhauling its legislation on climate, energy, and transportation, emphasizing the importance of the EU Emissions Trading System (ETS) as a pivotal tool for economically efficiently reducing greenhouse gas emissions and promoting a low-carbon future.

Additionally, the EU is exploring the implementation of a carbon adjustment mechanism to protect European industries from unfair competition, intending to enforce a carbon price on products imported from countries with less stringent climate regulations. This underscores the significance of uniformity in environmental policies. The EU is also advocating for the adoption of circular economy practices, a fundamental part of the Green Deal. The circular economy not only aims to reduce waste but also to encourage reuse and recycling, vital for sustainable resource and material management.

Globally, the United Nations' 2030 Agenda for Sustainable Development serves as a guiding framework for international efforts, covering 17 Sustainable Development Goals (SDGs). These goals address a wide array of issues, encompassing poverty eradication, enhanced education, improved health, gender equality, and action against climate change.[25]

In Finland, the government is committed to achieving climate neutrality by 2035, aligning its ambitions with global goals. The nation strives to lead in the circular economy, showcasing a strong dedication to sustainable environmental policies. Through innovative approaches and pilot projects, Finland has implemented strategies to reduce emissions and promote sustainability, serving as a model for tackling global environmental challenges.
Simultaneously, Finland's electricity demand forecast shows a consistent and moderate growth trajectory from 2010 to 2070. Starting at 83,4 TWh in 2010, decreasing to 78,4 TWh in 2015, and gradually increasing to 110,4 TWh by 2050, this trend could be influenced by various factors such as industrial developments, demographic changes, technological advancements, energy policies, and environmental considerations.[26]
Aligned with Finland's clean energy objectives, including the aim to achieve carbon neutrality by 2035, these forecasts are pivotal in energy sector planning. They enable the government, energy providers, and stakeholders to prepare for infrastructure investments, policy adjustments, and the integration of renewable sources to sustainably meet the projected increase in future demand, while advancing the country's transition towards a carbon-neutral energy system. This evolution is essential for ensuring a dependable and sustainable energy supply for the nation while aligning with its environmental objectives.

5.3 Climate change impacts

Climate change will affect the meteorological conditions in many aspects. In this section, the focus is made on Finland what those changes will be and how they will affect the different energy sources Finland uses to produce electricity and heat.

- **Temperatures:** The increases in temperatures in Finland are predicted to be between 2,3°C to 6°C by the end of the century. This will result to less frequent far-below zero temperatures, more warmer periods and a rise in the highest temperatures. Especially warmer winters in Finland will affect the country in many different ways e.g. the soil will be less frozen and its carrying capacity will be weaker.[27] [28]
- **Rainfalls, flooding and droughts:** It is predicted that amount of rainfall in Finland is going to increase 18-20% by the end of this century. One significant reason for that, is warmer winters. Due

to this, some amount of snowfall will come as a rainfall. Larger amount of rainfall also increases the risk of flooding. It is predicted that the runoff water risks will grow in every region of Finland.[29] On the other hand, because the summer will be warmer, the summer dry periods will extend.[27]

- **Wind:** There are a lot of uncertainties in predicting how climate change is going to affect in the wind in Finland. Some possible changes are that wind speed in autumn might increase. The simulations have also shown, that thunder storms in Northern Europe will increase 5-40% by the end of this century, therefore this might also affect in windiness of the summer time. However, it is possible to assume that there are not significant change in the windiness in Finland.[28]

- **Forests:** Forests are very important ecosystems in Finland and climate change will affect them in many ways. Especially in the northern part of the country, having more precipitations and less freezing will improve the capacity of the ecosystem and better nutrient loading in the soil. This may result in bigger yields in the forestry field. In addition, the less the soil is freezing in the autumn, the more forests are vulnerable to wind damages. However, warmer temperatures could also enable harmful organisms to spread.[27] [28]

5.4 Technologies developments

The development of technologies in a time span of about three decades can have a major impact on the efficiency and overall availability of various energy production sources. Therefore, the following presents assumptions for developing technologies with the presumably most significant effects on production rate deviations.

- **Heat Pumps:** Heat pump technology is already quite mature in today's world. While it is possible to anticipate some improvements in its efficiency by 2050, these enhancements are likely to be relatively modest, with just a few percentage points of gain. The efficiency of a heat pump is critically dependent on the source of heat it utilizes. During the winter, sources like the ground and external water tend to maintain higher temperatures compared to the ambient air, which means that ground-source and water-source heat pumps consume less electricity than air-source ones, resulting in a higher Coefficient of Performance (COP).
  In a country like Finland, where heating demands dominate, air-source heat pumps have gained significant popularity, accounting for at least 80% of the market. Historical trends suggest that air-source heat pump sales have outpaced other types. Therefore, roughly 80% of the efficiency of Finnish heat pumps can be attributed to outdoor ambient temperatures.
  Looking ahead to 2050, climate models indicate an expected temperature increase of around 1,5°C. This warming trend translates into a projected COP improvement for heat pumps of approximately 0,2 or roughly 6%. When combined with the anticipated technology efficiency gains of a few percentage points, it becomes plausible to assume that existing heat pumps in 2050 will yield about a 10% increase in their performance.[31] [32] [33] [34]

- **Solar power:** Currently, the average solar power module efficiency across all panel types stands at around 15%. By 2050, it is expected to soar, reaching an impressive 25% on average. However, this remarkable 67% increase in efficiency, while still making use of the same solar intensity and availability, cannot be directly translated into a 67% boost in predicted solar power production for 2050. The typical lifespan of solar panels falls within the range of 20 to 25 years, contributing to an effective efficiency increase of approximately 30%.
  Based on the average of four scenarios published by Fingrid, the production of solar power will be between 9-39 TWh by 2045. In the more ambitious scenario, the assumption of increased technical development would allow the solar power output to rise to around 12 to 51 TWh.[35] [36]

- **SMR:** Small Modular Reactors (SMR) aren't used currently in Finland. As an SMR is considered a reactor producing less than 300 MW of electricity. SMR's are planned to produce electricity, heat or both. Radiation and Nuclear Safety Authority of Finland (STUK) is preparing that Finland will have SMR's in the future.[37] Development of SMR's has been faster than expected in the past few years. Ongoing problem with Finnish legislation is that it is made for conventional nuclear power plants, which produce a lot of electricity and can be placed far away from residential areas. Especially SMR's producing heat for DH system would be placed close to residential areas and therefore the legislation would require major changes. So far STUK has given cautious nod towards building SMRs closer to residential areas.[38] There are several companies investing to build SMRs to Finland producing electricity, heat or both. Schedule of how fast the technology is mature and when the Finnish legislation is ready is the question.

- **Wind power:** Wind power can be separated in two sections - on-shore and off-shore. On-shore wind farms are a common sight in Finland. There is one off-shore wind farm in Tahkoluoto Pori with capacity of 44,3 MW. Off-shore capacity is 0,7% of the installed wind power capacity of Finland.[39]
  On technology point of view the capacity factor of wind power has increased. This is mostly due to bigger turbines and better efficiency. This can be assumed to increase, but not eternally. So at some point the the technology will be as efficient as possible.[40]
  Off-shore wind is a rather mature technology with possibility to have higher capacity factor than on-shore wind. Off-shore wind requires bigger investments than on-shore wind. The technology development would have to focus on reducing the price in order to make off-shore wind more profitable. In addition increase of off-shore wind would require favorable financial situation.

- **Hydrogen:** In Finland's most ambitious plans Finland would produce 10% of Europe's hydrogen production. Significant portion of hydrogen would be exported to Europe and therefore hydrogen is a consumer of electricity. Hydrogen can also play a role in balancing the electricity demand and production. Hydrogen electrolysis will also produce a lot of waste heat which can be used in district heating system. Electrification of industry is depending on how much hydrogen is produced in the future. Increase of hydrogen production would increase renewable electricity production.[41]

6 Updated Finnish roadmap 2023

This chapter presents the three different scenarios: **Slow**, **Assumed** and **Ambitious**. The differences between each scenario are based on different variations of assumptions presented in previous chapter. Lastly, the chapter discusses about emissions and how those are calculated.

6.1 Three scenarios modelled in the Finnish Roadmap 2023

Based on the assumptions presented in the previous section, three scenarios have been modelled: **Slow**, **Assumed** and **Ambitious**. This section presents the approach chosen for each of those three scenarios and details how the assumptions were defined in them.

Slow scenario

The "Slow" scenario is the scenario for which the transition towards carbon neutrality is the slowest. All assumption criteria are considered with the least favorable condition to progress towards low emitting energy sources. The interest rates are high in this scenario. This makes it difficult to invest and slows down new projects to produce energy such as new renewable energy power plants. High investment rates also induces a weaker development in new technologies.
The carbon prices are low. This, again, does not establish an environment that promotes a fast transition to reduce carbon emission since the price the emitting carbon sources have to pay are not as high as in the other two scenarios.
Regarding the impacts of the climate change, they are considered the most important in this scenario so all the predictions considers the biggest changes. The temperature increase will be close to 6 degrees Celsius, and the rainfalls and the thunder storms massively increase (respectively around 20% and 40%). Those changes have an important impact especially on how the forests grow and the hydro reservoirs are managed. Because, as detailed earlier in this report, biomass and hydro are two majors energy sources in Finland, climate change may have significant undesired effects.
Lastly, this scenario, considers minor technology developments in the next decades, leading to some increase in efficiency, thus a decrease in consumption but not a significant reduction due to those improvements.

This "Slow" scenario is the only one that does not reach carbon neutrality for Finland in 2035. Indeed, in this scenario, the carbon neutrality is reached in 2040.

Assumed scenario

The "Assumed" scenario is in between the "Slow" and "Ambitious". It considers the four assumptions with moderate interest rates, carbon prices and climate change impacts. This means that although the investment environment is more favorable than the one depicted in the previous scenario, the interest rates would remain around 2% in the next decades. The same logic applies for the carbon prices, they are higher than in the "Slow" scenario which encourages more transition towards less emitting energy sources.
The climate change impacts are still important in this scenario and affect mainly the biomass growth and the hydro production but in less important scale than in the "Slow" scenario.
Finally, the technology developments are more important than in the previous scenario. This leads to more efficient technologies and an overall decrease of energy consumption.

Ambitious scenario

The "Ambitious" scenario is the one that is has the most optimistic assumptions out of the three scenarios. For the reasons detailed above, it considers low interest rates, high carbon prices, more manageable climate change impacts (although they are still present) and fast developments of new and existing technologies. All these assumptions results in Finland reaching carbon neutrality in 2035.

Summary of the assumptions considered in each scenario

The table 1 below summarise how the four assumptions apply to each scenario.

Table 1: Comparison of the assumptions for each scenario of the Finnish Roadmap 2023.

	Slow	**Assumed**	**Ambitious**
Interest rates	High	Moderate	Low
Carbon prices	Low	Moderate	High
Climate change impacts	Aggravated	Moderate	Mild
Technology developments	Slow	Reasonable	Fast

6.2 Scenario Slow progression

6.2.1 Power production

Power production will significantly increase in the next decades. This section details how it will increase in case of the "Slow" scenario.

Electrification

It is assumed that the overall electricity consumption will increase in Finland (Figure 12), mainly due to the industry and this will happen even in the slow scenario. In 2035, the electricity consumption is expected to rise to around 106 TWh and up to 142 TWh for 2050. These estimation are based on the orad-maps produced by Finnish Energy and Fingrid. In this scenario, the consumption is expected to increase by 2% annually and an annual decrease of 578 GWh of net import leading to a total domestic production of 100 TWh in 2035 with 6 TWh of net imports and a phase-out from imports in 2044.

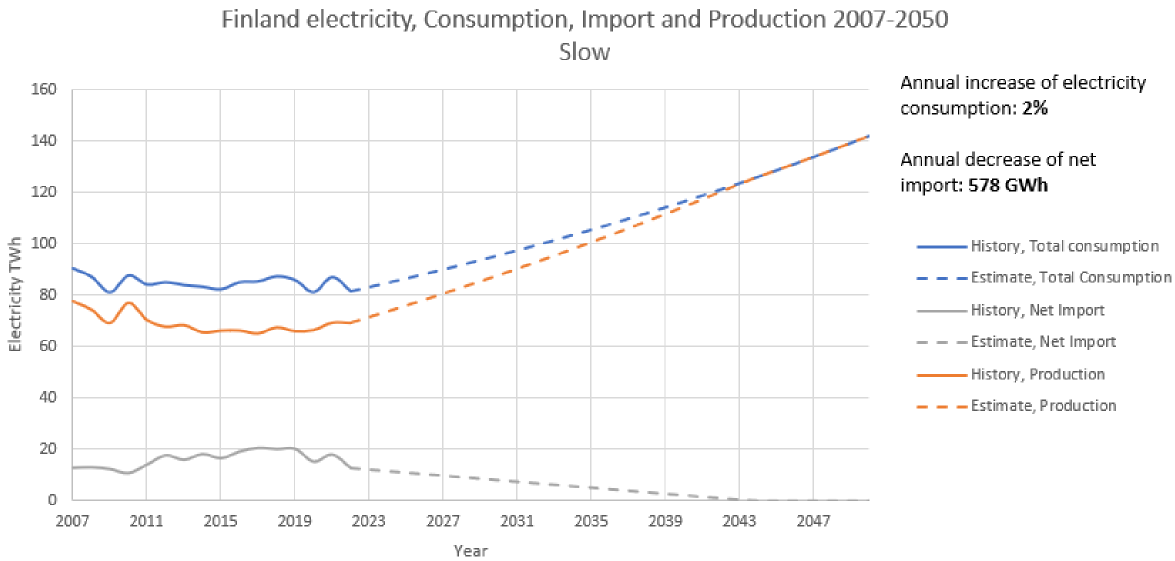

Figure 12: Finland consumption, import and production of electricity 2007-2050 (slow progress).

Hydro

The forecast for 2035 shows that the installed capacity for hydro power will increase slightly to reach 10% of the total power capacity but no other hydro power plants will be built as the hydro sector has reached its max capacity in the country. However, what could happen due to climate change would be the change is the seasonal distribution due to the increase in temperature. At the moment, reservoir are filled from spring through autumn to guarantee enough water during the winter times. Climate change would impact that seasonal distribution as heavy rainfall could happen not only in spring as it is the case today but also during the summer or fall and even in winter when the reservoir are usually full. This would affect long-term planning of hydro power making it more difficult to use. [42]

Solar

Solar energy will increase in the next decade as the technology has a good potential in Finland and has not been developed much yet, as the current production is around 0,4 TWh. There are already multiple on-going solar power projects and therefore the solar energy production is expected to reach 6 TWh in 2035 and 8 TWh in 2050 in this scenario. Increasing solar power production is an important step towards low carbon future as it help reducing the share of fossil fuels in the energy mix.

Wind

The high interest rates will slow down the investment in the wind sector, delaying current projects and maybe even stopping some of the planned projects due to lack of investments. Nonetheless, new projects could arise in the future to replace the cancelled ones. Wind is separated in On-shore wind and Off-shore predictions as they differ depending on the period.

- Offshore Wind Energy: There are many on-going projects for off-shore wind power which will lead to an increase in produced electricity. The nominal power is expected to increase by 15% yearly resulting in an electricity production of 7 TWh in 2035 and 24 TWh by 2050. Off-shore wind power will mostly increase during the period of 2035-2050.

- Onshore Wind Energy: Onshore wind has already started to grow rapidly in the recent years and the trend show it will stay that way in the next decade. An annual increase of 30% is expected leading to an electricity production of 27,5 TWh in 2035 and around 45 TWh for 2050.

Overall the wind power production will grow to 35 TWh in 2035 and 69 TWh in 2050, playing a major role in achieving carbon neutrality for Finland. It will also help the decarbonisation of the industry as more green energy will be available.

Nuclear

Nuclear energy currently accounts for 30% of the energy share in Finland and it will be brought up to 40% with the launch of the Olkiluoto 3 reactors in 2023. The previsions shows that Finland are not planning on opening new nuclear power plants or closing nuclear power plants in the near future, thus the share of nuclear energy is likely to stay the same. Due to the lack of interest on SMR technology and the current high interest rates hindering the development of the technology, this scenario considers that no SMR project for electricity production will get under way before 2050.

Biomass

The majority of Biomass will be used in heat production to reduce the share of fossil fuels, the rest of it will be used in electricity consumption as a peak load solution and as the bi-product from the heat production. The share of biomass will reach 12 TWh in 2035 and 15 TWh in 2050.

Import and Export

Due to the delay in wind power projects, Finland will need to compensate the lack of energy by importing from neighbouring countries to avoid using coal, natural gas, oil and peat. As mentioned in the Electrification part, imports will still play a role in 2035 and account for 6 TWh of the electricity production to meet the demand. However, a phase-out from imports is expected by 2044 and thus there would be no import in the energy mix in 2050.

Hydrogen

High interest rates will slow down the development of green hydrogen reducing the capacity production which will be closely related to the development of wind power. Furthermore, Hydrogen is not considered as an energy source for Finland but more as a product from the industry as the increase of energy production is mainly due to the increase of energy demand from the industry.

Summation for power

The Figure 13 below shows the total amount of power production in the slow scenario for 2035 and 2050 with the production of 2022 as a reference.

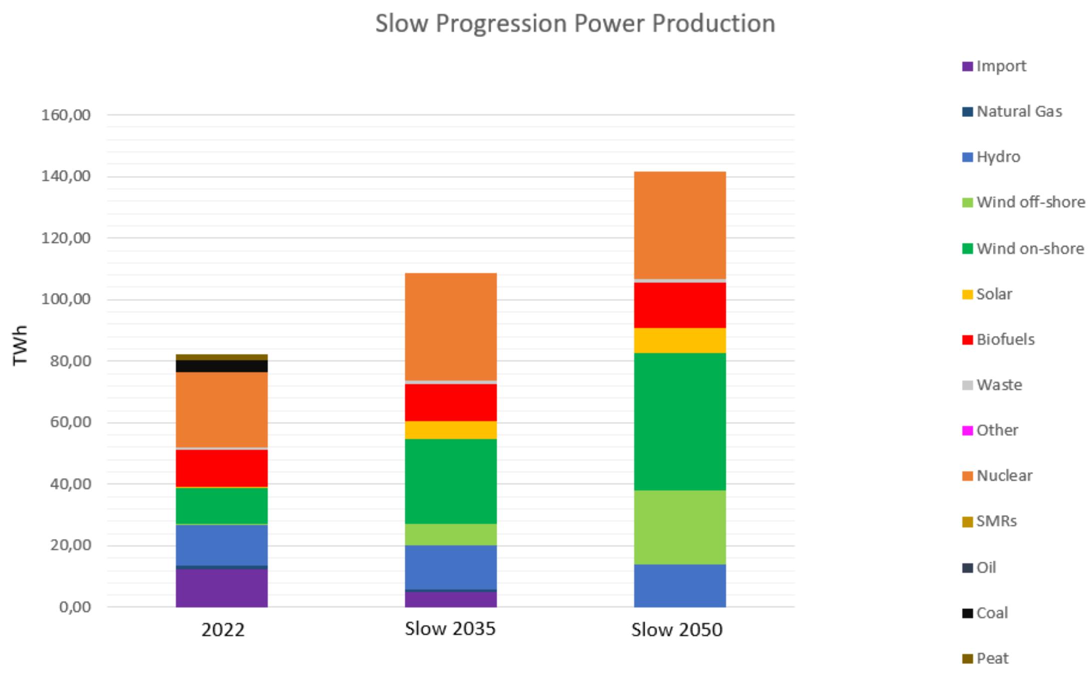

Figure 13: Power production in slow scenario.

It can be seen that there are still imports and natural gas in 2035 but they are not present in 2050. The power production rise by 32% compared to 2022 by 2035 and 73% by 2050 with a rapid increase in wind and solar.

6.2.2 Heat production

The slow progress scenario assumes the least optimistic position towards the assumptions mentioned above. In terms of heat production, the different energy sources will evolve as described in the categories below.

Biomass and fossil fuels

In 2022 fossil fuels play a major role in heat production with 33,8% of the total energy sources used. Coal is the fossil fuel resource that will observed the biggest change. Indeed, Finland decided on phasing out of coal for 2029. Peat and natural gas will also decrease but will remain in smaller proportions in 2035: around 8% of the heat production will still rely on those fossil fuels. In 2050 all fossil fuels will be phased out.
Biofuels, forest fuels and wood waste are resources that are vastly used currently. Because they emit CO_2, they will decrease in the future. The slow scenario does not implement any new technology such as small modular reactors (SMRs) nor any major efficiency improvements. This results in small decrease in heat production and slow transition to the reduction of those sources. In 2035, biofuels combined with forest fuels and wood waste constitute 38,9% of the heat production and it decreases to 31,9% in 2050. This shows the key role of those energy sources in the slow scenario.

Waste heat and waste incineration

Waste heat is planned to increase because of its huge unused potential currently. Finland already has a huge district heating network and can use waste heat to its advantage. In the slow scenario, waste heat will increase from 4,9 TWh in 2022 to 7,5 TWh in 2035 and 9,5 TWh in 2050.
On the other hand, waste incineration would see a slight decrease from 3,1 TWh to 3,0 TWh in 2035 and would remain constant from then until 2050. This slight decrease can be due to improved recycling chains leading to overall less waste.

Electricity

Electrification is a major component of the low carbon strategy for Finland in the next decades. The coal phase out will mostly be compensated with the electrification of the heat production as it will increase from 0,5 TWh in 2022 to 10 and 11 TWh in 2035 and 2050 respectively. This electricity will be used in electric boilers and different heat pumps technologies.

New technologies

In this scenario, the SMRs see their implementation do not materialise due to economic reasons. Because the interest rates are high, the SMRs are not beneficial enough to be invested in for 2035 nor 2050.

Geothermal heat production is another technology that has not been successfully implemented in Finland yet. This scenario assumes no production of heat thanks to geothermal will be pursued in the newt decades. In the past, several trials have been unsuccessfully made regarding geothermal heat production and it is assumed here that the situation will remain the same.

Summation for heat

The Figure 14 below shows the total amount of heat production in the slow scenario for 2035 and 2050 with the production of 2022 as a reference.

The decrease of the overall consumption is the smallest of the three scenarios with a decrease of 2,4% for 2035 and 3,1% for 2050. This is partly due to not much gain in efficiency in the different technologies used. The biofuels will also remain important in this scenario to be able to phase out of the fossil fuels without new technologies available such as SMRs or geothermal heat production.

Overall this scenario reaches carbon neutrality[1] in 2040 instead of 2035 for the two other scenarios. This is mainly due to the electrification and the increase of use of waste heat.

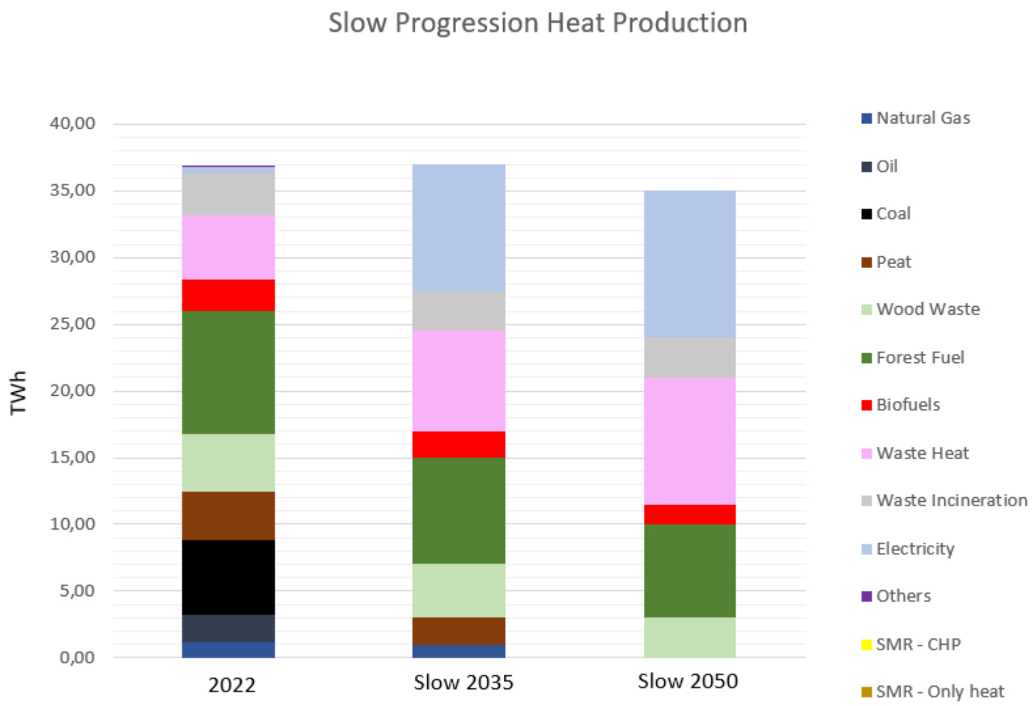

Figure 14: Heat production in slow scenario.

[1]Thanks to carbon sinks not considered in this report to compensate the remaining emissions.

6.3 Scenario Assumed progression

The assumed scenario is considered as the most realistic one from these three scenarios. The assumptions for this scenario are detailed above, this section focuses on how they affect the power and heat production.

6.3.1 Power production

This part discusses how electrification will change and what power methods are used to cover the consumption in assumed scenario.

Electrification

The industry is assumed to electrify and the overall consumption of electricity will increase. This is required in order to end usage of fossil fuels in the industry. Overall electricity consumption of Finland in 2035 is assumed to be 136 TWh and in 2050 around 245 TWh. This will increase the demand for fossil-free electricity. The Figure 15 presents the electrification increase in assumed scenario.

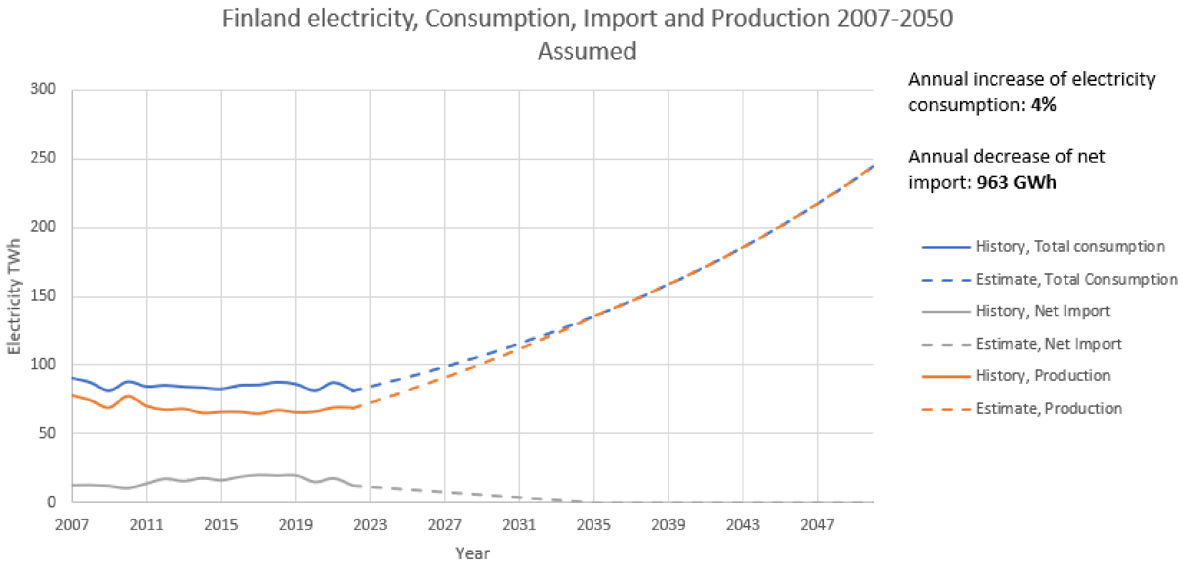

Figure 15: Finland consumption, import and production of electricity 2007-2050 (assumed progress).

The estimates for electricity consumption are based on the road-maps produced by Finnish Energy and Fingrid. The graph includes historical data during 2007-2022 from Finnish Energy statistics.[43] The estimates are calculated with an annual increase of 4% for electricity consumption and 963 GWh of annual decrease of net import. Decrease of net import is based on that by year 2035 it would be zero and annual part is calculated with linear approximation.
One of the most significant factors in future electricity consumption in this scenario is production of green hydrogen. In this scenario the production of green hydrogen will increase to match with domestic consumption. The domestic use of hydrogen is increasing at the same time as industries are eager to use hydrogen instead of fossil fuels.

Hydro

Hydro power is seen as an important energy source that can be adjust to meet the current energy demand, and therefore all current plants continues producing power. As stated in previous scenario, the hydro plant capacity in Finland has already been reached. However, it is assumed that the investment environment is favorable to develop plants more efficiently.
Also, due the warmer winters and increased rain falls the water amount for power production increases. Therefore hydro power remains also as important adjustment force in power sector with estimated production 14 TWh in 2035 and in 2050.

Solar

In the coming years solar power capacity in Finland will increase rapidly. It is assumed that investments to industrial scale solar power plants increases, and those are focused for new plants and to expand current power plants. Currently Finland has industrial scale power plants under construction phase with estimated power almost over 2 TWh.[44] In this the assumed scenario, the production is able to reach 9 TWh in 2035 and even 15 TWh in 2050. These number are covered by both larger and smaller scale solar power parks.

Wind

In this scenario,it is assumed that wind power will significantly increase in Finland to cover the power demand. This is mostly because new projects, since it is expected that amount of the wind does not increase in Finland due to climate change impacts. With moderate interest rates, the investments will focus more on-shore wind farms than off-shore wind farms.

- Off-shore wind energy: Currently, there are only small amount of off-shore production in Finland, which is mainly covered by Tahkoluoto wind farm. The potential of off-shore wind farms has been recognized, and therefore there are many projects on-going to increase the off-shore capacity. In 2035 the amount of off-shore production is approximately between 18 and 19 TWh, and in 2050 it is assumed to increase to 68 TWh.
- On-shore wind energy: As mentioned, the on-shore wind farms will cover more power demand than off-shore wind. One reason for this, is that cost are more lower and the interest rates affect to investments. In this scenario, is assumed that in 2035 the on-shore wind power production is over 40 TWh and in 2050 it will be over 81 TWh.

Nuclear

Finland has currently five conventional nuclear reactors producing only power. The nuclear power plants are assumed to produce electricity with full power until 2050 with current capacity factors. These reactors would produce 35 TWh of electricity annually. In the assumed scenario SMR's are considered to develop so the first ones would be operating before 2035. By 2035 there would be two 200 MW SMRs. With capacity factor of 92% they would produce 3,2 TWh of electricity. By 2050 there would be six 200 MW SMRs producing 9,7 TWh of electricity annually. Loviisa nuclear power plant has permit to operate until 2050.[45] The new SMRs would replace reactors shut down and ensure stable energy source also after 2050.

Biomass

Regardless of the production method, the biomass is seen as a renewable energy source. However, the used biomass must be sustainable produced to meet the RED2 directive.[46] Biomass can be also seen as in big role to meet the peak demand especially in winter. In the assumed scenario, it is expected that there will be small increase in this production method, since the production will meet 15 TWh in 2035. After that, there is no expected increase in biomass power production.

Import and Export

The investment in Finland drives the transformation from fossil fuels towards green energy production. The potential of new projects in wind and in solar has been recognized and used to accomplish the production to meet the demand. Therefore, Finland is able to become net-zero importer in power. However, is still assumed that there will be import and export with Sweden, Estonia and Norway. This will guarantee that the peak demands can be meet, but is also exported as much power that is imported.

Summation for power

The Figure 16 presents estimated total amount of power production in 2035 and 2050, with reference data from 2022.

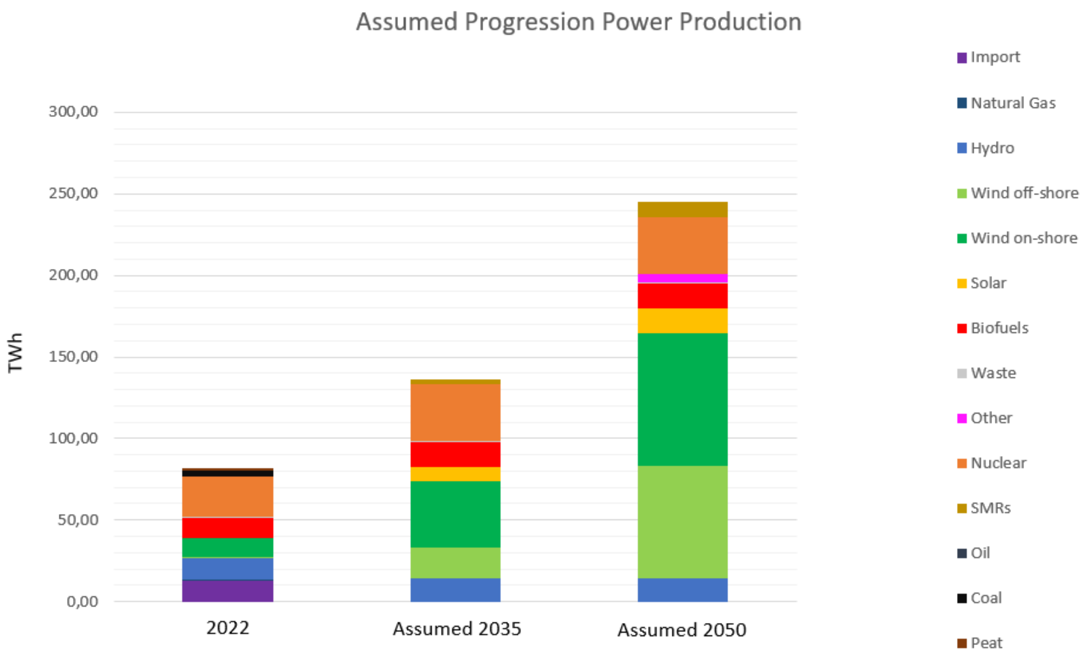

Figure 16: Power production in assumed scenario.

As presented in the figure, the power consumption in assumed scenario in 2035 is over 135 TWh and in 2050 it is near 245 TWh. The amount of wind power will increase rapidly, and use of fossil fuel is phase out before 2035. To be mentioned, the increase in solar power is significant, however the share in total production is not that large when compared to wind power.

6.3.2 Heat production

This part discusses different heat methods that are considered as the most significant part, to be able to phase out from fossil fuels.

Combined Heat and Power

Combined heat and power plants (CHP) have played major role in Finnish heat production. In 2022 fuels used were fossil fuels (Natural Gas, Oil, Coal and Peat), forest fuels, wood waste, biofuels and waste incineration. They are also used in heat only boilers but majority is used in CHP's. These plants are based on burning some fuel which causes emissions. Therefore especially usage of fossil fuels should be ended and others reduced. In this assumed scenario fossil fuels are used only as reserves in 2035. Fuels used are peat and natural gas with 2,8% portion of total heat production. The complete phase out from fossil fuels would happen before 2050. Waste incineration would reduce due to lower amount of produced waste. Increase of recycling - especially plastic would reduce the total amount of generated waste. Small Modular Reactors can work also as CHP plants and in this scenario they replace bio-based fuels in order to have less emissions.

Waste heat

Heat is used as a commodity in various ways. However, it is known that a lot of heat is not fully utilized which means that there is a lot of unused potential. Recently, it has been suggested that temperature in district heating network should be lowered below 100 Celsius for efficiency usage of waste heat.[47] Thus, it is assumed that this has taken considered in the future. The heat production with waste heat is estimated to be 9 TWh in 2035 and 10 TWh in 2050.

Electricity

Electricity can be used in heating with many ways like heat pumps or boilers. This sector includes all electricity used in order to produce heat. As the power production of Finland is no longer using fossil fuels electricity is considered as a green source for heat. Heat only electric boilers are able to heat water enough hot for district heating systems. Boilers could also heat water in storages when price of electricity is low. This method would also balance the electricity market. The heat production with electricity is estimated to be 11 TWh in 2035 and 12 TWh in 2050. This is significant increase since for 2022 it was only 0,5 TWh.

New technologies

To lower carbon emissions in heating sector, the new technologies are in significant role. Currently, Finland is seeing potential in SMR's with future heat production, but confirmed investments is not done. Due to moderate interest rates, the investments will be done and first commercial SMR's are assumed to be in production in 2035. The letter of intent between Steady Energy and Helen, aids this assumption. Also, in this scenario it is assumed that in 2050 the SMR's have been commercialized and at least Helen's planned ten 50 MW SMR's are in production. The total nuclear power in heat sector is estimated to be 38,05 TWh in 2035 and 44,50 TWh in 2050. In these numbers both SMR only-heat and SMR CHP are taken considered.

As stated in the slow progress scenario, the geothermal production is not commercialized in Finland in 2035.

Summation for heat

The Figure 17 presents the total heat production in assumed scenario in 2035 and 2050, with reference data from year 2022.

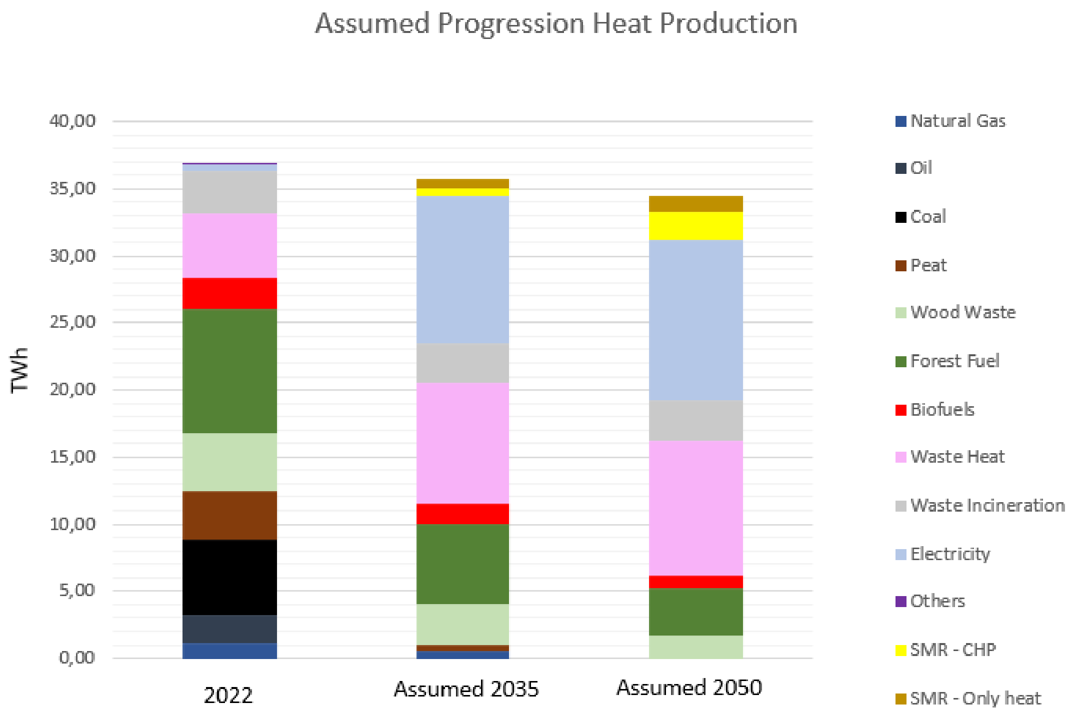

Figure 17: Heat production in assumed scenario.

As the figure presents, the total amount of heat production will decrease in assumed scenario. In 2035 the assumed total amount of produced heat is 35.68 TWh and in 2050 34.40 TWh. To be able to phase out from fossil fuels, the heat production with electricity and waste heat is assumed to increase to cover the demand. In 2035, there are still small amount of peat and natural gas, but those are seen as reserve to cover the possible peak demands. As a new technology, the heat production with small modular reactors is reached in 2035.

6.4 Scenario Ambitious progression

6.4.1 Power production

Within the ambitious scenario, the evolution of energy in Finland unfolds in a context characterized by low-interest rates, fostering significant investments and substantial progress towards climate goals (Figure 18). In this optimistic perspective, the investment-friendly environment acts as a catalyst to enhance the competitiveness of sustainable energy sources.

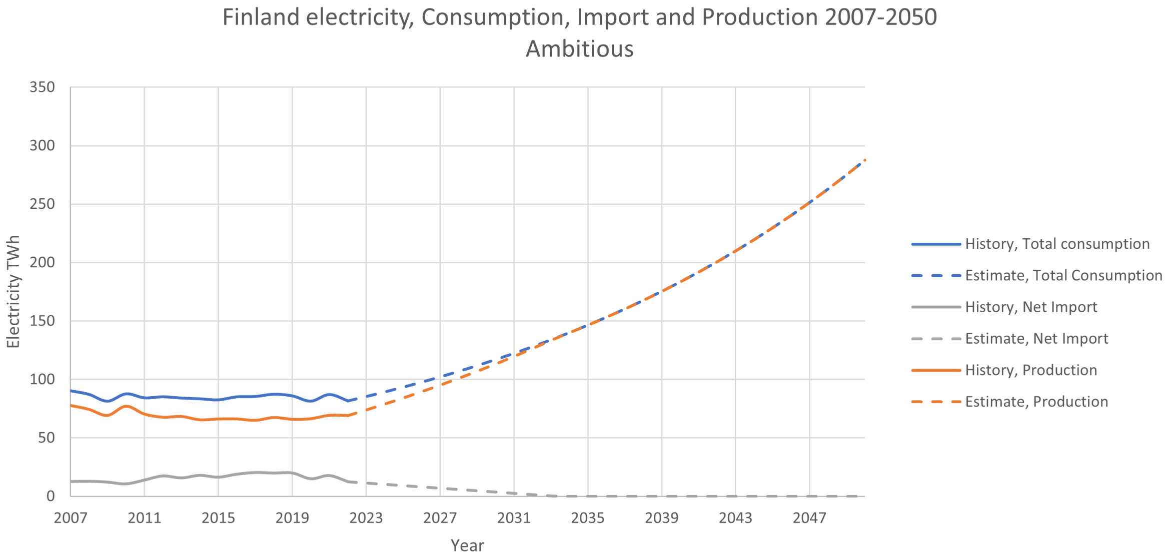

Figure 18: Finland consumption, import and production of electricity 2007-2050 (ambitious progress).

Hydro

Hydropower, recognized as the second-largest contributor to Finland's electricity mix in 2022, stands out as a dependable and emission-free component of the power sector. While there may be limited room for growth in hydropower, it is virtually certain that no new hydro plants will be constructed in Finland by 2050. This restriction is imposed by the Wild River Act, which prohibits the establishment of new hydropower facilities to safeguard the natural environment. Consequently, the anticipated production rate remains at approximately 14 TWh, mirroring the 2022 levels. As a result, the focal point for hydropower in Finland over the coming decades shifts towards the revitalization and enhancement of existing hydropower installations.[48]

Solar

In terms of solar energy, Finland has more ambitious plans, with the International Renewable Energy Agency (IRENA) suggesting that the cumulative installed capacity of photovoltaic solar could reach 8,6 GW by 2050.[49] This would position solar as one of the the most important renewable energy source, following wind. Notable solar future projects include the Mustaisneva-Rojunneva, Kauhajoki (pre-examination phase, size 600 MW) and Suursuo & Huuhansuo, Lappeenranta (authorization phase, size 600 MW) solar plants.[44]

Despite these aspirations, Finland faces challenges in its solar energy endeavors. These challenges include the country's geographical location, adverse climate conditions, high initial costs, existing energy infrastructure, and energy policies.

To encourage solar energy adoption, Finland has implemented a tax incentive system. Self-consumption of solar energy is exempt from grid charges and electricity taxes, with businesses and municipalities eligible for subsidies ranging from 24% to 40% for photovoltaic investments. [50] However, these incentives do not currently extend to residential buildings and construction companies.

All mentioned assumed development for solar power lift production rates up to around 20 TWh for the ambitious scenario in 2050.

Wind

For 2050, Finland has ambitious plans for both offshore and onshore wind energy. The assumed production rates are hereby separated in offshore and onshore predictions in the ambitious scenario.

- Off-shore wind: Recently, the Finnish government has granted permits to lease its seabed for the development of two large off-shore wind farms. The Tahkoluoto wind farm, currently the only one in Finnish waters, could be expanded with up to 45 turbines, reaching a total capacity of 900 MW. Another area, Korsnäs, located further north in the Bothnian Bay, could have a capacity of up to 3 GW.
  It is important to note that the European Union's strategy aims to increase off-shore wind energy capacity to at least 60 GW by 2030 and then to 300 GW by 2050. This would be a 25-fold increase from the current capacity of 12 GW over the next 30 years. Therefore, Finland, as a member of the EU, will certainly contribute to achieving this goal contributing to the off-shore wind target of not less than 20 GW (nominal power) by 2050.[51] This installed power capacity leads to an overall power production of off-shore wind energy to around 82 TWh for the ambitious scenario.

- On-shore wind: Over the past decade, Finland has significantly increased its on-shore wind energy capacity. Wind energy now constitutes over 10% of Finland's electricity, a notable increase from less than 1% a decade ago. By 2025, wind energy is expected to meet at least 27% of the country's electricity needs.
  A recent study estimates that extensive electrification of the Finnish economy would increase electricity demand by over 20% by 2035. By 2050, Finland's annual electricity consumption would double from the current level, reaching nearly 170 TWh. To meet the increase in consumption, Finland's electricity production from wind on-shore sources would be more than 90 TWh by 2050. In the main case, most of the new generation would be on-shore wind energy, which is a cheaper way to produce electricity compared to other zero-emission generation technologies. The share of combined on-shore and off-shore wind energy in Finland's electricity generation would rise to over 60% by 2050, up from about 10% in 2020.[51]

Nuclear

Nuclear energy holds a key position in Finland's energy landscape, playing a crucial role in the government's pursuit of carbon neutrality and reduced energy import dependence. In 2021, nuclear energy contributed to around 30% of the total electricity production, and this share is anticipated to surpass 40% with the launch of the Olkiluoto 3 reactor in 2023, marking the first new nuclear plant in Europe in 15 years.[52] [53]
Looking ahead, Finland envisions maintaining a substantial nuclear energy share while increasing the role of renewable energy sources in electricity and heat production. For the ambitious scenario in 2050 the construction of new traditional nuclear power plants is not expected due to the progressively high saturation in the power market and extreme high construction costs and time.
However, the maturity of SMR-technology is expected to be reached earlier in the ambitious scenario, which assumable raises the nuclear power production rates by around 16 TWh to in total 51 TWh in 2050. A large share of the yet to be built SMRs will be combined heat and power plants, which not only benefits the decarbonisation in the heat sector, but also lifts the nuclear-based power production to new heights.

Biomass

Finland, with its wide and large forests, holds substantial potential in biomass energy production. In an ambitious scenario for 2050, Finland could maximize biomass utilization for electricity generation, involving the expansion of existing projects and investments in advanced technologies to enhance efficiency. The good investment environment supports maintaining the status quo, significant expansion of biomass production capacity, and massive investments with research and development into novel technologies.[54]
However, the substantial part of biomass will be used as a replacement of fossil fuels in heat production. Consequently, and since other more sustainable energy sources are available, the role of biomass for the power sector is targeted to be reduced to peak load solutions and as a bi-product in CHP-plants intended for heat production.
Anyhow, it is crucial to manage biomass energy production sustainably to avert adverse environmental impacts, integrating it into a broader energy mix that includes sources such as wind and solar.
Although biomass will remain a part of electricity consumption by 2050, the production rates will shrink

inversely proportional to approximately 15 TWh, considering Finland's aim to double annual electricity consumption by 2050.[55]

Import and export

Finland, showing a deficit of power production in 2022, relies on imports for its energy needs, and aspires to achieve carbon neutrality by maintaining nuclear energy, boosting renewable energy sources, improving energy efficiency, and electrifying sectors like industry and transportation. In an ambitious scenario with low-interest rates, net energy imports might become redundant, potentially allowing Finland to diversify energy sources further and to heavily invest in new RES electricity production capacities. Already in 2023, more accurately since late March 2023, Finland has been generating more electricity than it needs, and thus has been a net exporter of electricity. This occurrence has not only to do with reduced power consumption due to energy saving attempts and a decline in manufacturing, but especially with added capacities from the nuclear power plant "Olkiluoto 3" and significantly more wind power production.[56]

These developments and plans lead to net-zero power imports in Finland in 2050, compared to an import rate of close to 13 TWh in 2022. It is crucial to note that plans around being a net-zero power importer may evolve based on various factors, including shifts in global energy policies, technological advancements, and economic trends.[15]

Hydrogen

In the projected 2050 scenario, Finland emerges as a pioneer in the hydrogen economy, contributing 10% to the EU's supply.[57] [58] Collaborative efforts between Fingrid and Gasgrid Finland lead to advanced infrastructures for clean energy, including electricity and hydrogen transmission. This collaboration, supported by Business Finland, is crucial for solidifying Finland's leadership in the European hydrogen landscape by 2050. [58]

In essence, both hydrogen and electricity production are pivotal for Finland's climate goals. Hydrogen production relies on competitively generated clean electricity, complemented by planned wind energy capacity expansion. Finland's strength lies in its clean, reliable, and economically viable electricity in the hydrogen economy. While anticipating a doubling of electricity production by 2050, these elements collectively play critical roles in achieving climate objectives, with hydrogen production contingent on the availability of clean electricity, and electricity production set to escalate to meet rising demand.

In the ambitious scenario for 2050, hydrogen is not considered as an energy source to cover production rates, but rather as an export product and power market balancing asset. Therefore, there are no direct production capacities allocated to hydrogen in 2050.

Summation for power

In essence, the Ambitious Scenario paints a picture of Finland's energy future characterized by innovation, technological advancements, and a commitment to sustainability. The successful realization of these ambitions hinges on a combination of favorable economic conditions, strategic investments, and continued efforts to overcome challenges in various sectors. As Finland navigates its path toward ambitious climate objectives, the synergy between clean electricity production, renewable energy sources, and emerging technologies will play a pivotal role in shaping the nation's energy landscape by 2050.

Conclusively, taking all efforts for each individual power source into account, the power production rate increases by a staggering 241% to a total of around 280 TWh for the ambitious scenario in 2050.

To visually represent the ambitious scenario, the following bar chart (Figure 19) illustrates the anticipated growth in power production from various sources in Finland, comparing the years 2022, 2035, and 2050. The black and red bars represent the power production (in TWh) for 2035 and 2050, respectively, based on the previous roadmap.

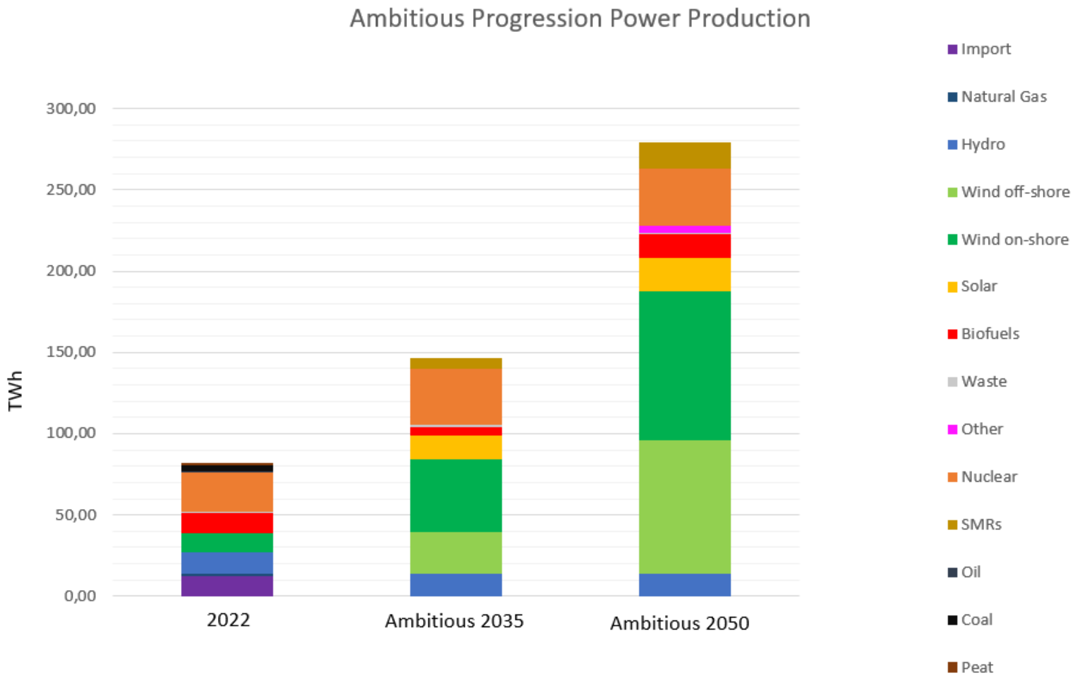

Figure 19: Power production in ambitious scenario.

This graphical representation provides a comprehensive overview of the ambitious scenario's impact on Finland's power production landscape, showcasing the evolution of different energy sources over the specified time frame.

6.4.2 Heat production

For the ambitious scenario, the identified assumptions and insights from previous chapters need to be incorporated for each heat source. The base assumptions for this scenario are as follows: Low average interest rates, high carbon prices, stricter regulations, incentives, and subsidies promoting RES, mild climate change, enhanced technology development, and steep growth in GDP. Consequently, the impact of the assumptions is due to be assigned to the corresponding heat sources and transformed into a numerical value to build comprehensive results.

Biomass and fossil fuels

In 2050, Combined Heat and Power (CHP) systems will harness sustainable biomass sources such as forest fuels, industrial wood waste and biogas. On the contrary, conventional sources like natural gas, peat, oil, and coal are completely excluded due to their non-regenerative properties.

The slower pace of climate change is anticipated to bring just moderate increased precipitation, reduced freezing, and extended growing periods, all contributing to slightly increased forest reproduction rates and biomass yield. In addition, the winter heat demand is expected to decrease modestly.[30]
Since these effects will not have a large impact on the biomass sector, it is unlikely that the production rate will surpass the baseline assumptions. This holds particularly true, given estimates that the yield from sustainably harnessing forests cannot be further increased compared to the present.

The diminished winter heat demand may result in a reduction in overall biomass usage. This trend is further reinforced by stringent regulations and incentives promoting Renewable Energy Sources. Biomass, despite being a regrowing resource, is not considered entirely carbon-neutral due to the processes involved in its harvesting, transporting, and planting. On the other hand, biomass could contribute better to the carbon neutrality target, if it is used as sustainable construction material. This way the captured carbon would stay locked up inside the biomass.

In conclusion, the out-phased production capacities coming from fossils are not one-to-one replaced by biomass in the ambitious scenario, but mostly by waste heat, electricity and new technologies. As a result, the biomass-based heat production for the ambitious scenario is projected to fall to only about 1 TWh in 2050, containing of each 0,5 TWh for industrial wood waste and forest fuel. At the same time, conventional fuels like natural gas, peat, and coal, but also bio-fuels, are completely phased out.

Waste heat and waste incineration

In 2050, the waste heat-based heat production is expected to be primarily derived from industrial processes, data centers or sewers utilizing heat pumps to ensure high temperature levels for district heating networks.

The already thriving environment for technology-specific development will be further enhanced by low average interest rates and substantial GDP growth. This conducive atmosphere is anticipated to result not only in the increased heat production by industrial waste heat, but also in the implementation of large-scale heat pump systems with heightened efficiency, attributed to an improved Seasonal Performance Factor (SPF).[32]

Simultaneously, the prevalence of waste heat-based heat pumps within Finland's heat source mix is projected to be elevated due to high carbon prices and subsidies promoting heat pumps as alternatives to biomass use or electric boilers.[31]

In conclusion, as the usage of heat pumps and industrial waste heat is increased in Finland based on these assumptions, waste heat-based heat production for the ambitious scenario is projected to be approximately 12 TWh.

In the context of waste incineration, the anticipated trajectory unfolds as follows: In the year 2022, the energy output from waste incineration is projected to reach around 3,1 TWh. Looking forward to the ambitious goals set for 2035, the target is to maintain a steady yet slightly reduced level, aiming for a waste incineration output of 3 TWh. As the progression continues toward the more distant horizon of 2050, ambition intensifies, with a goal to further curtail waste incineration to 2 TWh.

Electricity

In a fully decarbonized power market, a milestone likely to be achieved well before carbon-neutrality of district heating, electric heating in form of Heat-only Electric Boilers (HOBs) emerge as a viable solution for small and remote networks and to manage peak loads. This technology is known for its simplicity and effectiveness, directly converting electricity into heat.

In addition, heat pump technologies such a seawater, ground-source or air-source heat pumps are considered as electricity-based energy sources. Other than for HBOs, those heat pumps may contribute largely driven by the same assumptions as for waste heat-based heat pumps in the ambitious scenario.

The SPFs of those heat pumps are expected to be further boosted by higher annual average temperatures, particularly noteworthy given that four out of five heat pumps operate based on air-source principles. This climatic advantage is poised to contribute significantly to the overall efficiency of heat pump systems.[34]

Given the accelerated decarbonisation of the electricity-mix and progressively enhancing efficiency of heat pump technologies, the identified ambitious assumptions point towards largely increased electricity-based heat production rates in the range of 13 TWh, including a small 1-2 TWh participation coming from HOBs. This can be considered a quite steep incline, stating that electricity as a source for heating was nearly missing as a contributor to the heat-mix in 2022.

New technologies

When it comes to new technologies in an ambitious scenario for Finland in 2050, there are currently two main solutions being discussed: Deep geothermal energy and Small modular reactors. Until 2022, geothermal heat production wasn't a part of Finland's heat energy market.

Looking ahead to 2050, the deep borehole solution-based technology is being considered as a potential new energy source. However, deep geothermal energy projects in Finland face challenges due to the stable yet low-temperature bedrock - even in depths of more than 6 km. The need for drilling to considerable depths poses technological hurdles, with issues in both drilling and bedrock analysis causing delays and setbacks. Finland's unique geological requirements and the immature drilling technology

contribute to significant risks in ongoing projects.[59] [60]
In this context, it can currently not be assumed that geothermal will be seen in Finland for the upcoming years. However, it is worth noting that deep geothermal energy is expected to benefit from an improved technology development environment. In this context, some estimates predict that market maturity for geothermal energy use can be reached within a decade from today for the use in locations with better deep geothermal potential compared to Finland.

On the long term, the technology would be getting an extra boost from low average interest rates, high carbon prices, subsidies supporting RES, and a flourishing economy in Finland. Geothermal heat has many benefits, because it's not affected by climate change and is inexhaustible, making it a dependable source of long-term energy. All these factors collectively position geothermal heat as a somewhat not significant heat source for 2050 and heat production rates can be neglected.

Shifting the attention towards the second new technology, SMRs, a potentially novel addition to the Finnish heat market. Much like deep geothermal boreholes, SMRs stand to gain from the same ambitious assumptions, including advancements in technology, low interest rates, a strong economy, and elevated carbon prices.
In addition, they do not only produce heat, but can also contribute to the electricity market. The optimistic assumption is that the first operational SMR could be in place as early as 2030, serving as a key component in this scenario and contributing to an increased share in the heat mix for 2050 compared to a more conservative projection.

It is worth noting that the absence of deep geothermal heat might lead to higher shares for SMRs and vice versa.[37] [38] Considering SMRs only, the ambitious share in the heat production market is estimated to be around the 6 TWh mark, which would make this technology with a share of roughly 18% an important part of the heat production for the ambitious scenario in 2050.

Summation for heat

In conclusion, district heat production is anticipated to hover slightly lower, at around 34 TWh, compared to 2022 (37 TWh). The use of regenerative biomass will continue to be a part of the heat-mix, albeit with a clearly diminished significance.
However, the ambitious projection indicates that waste heat-based solutions, electricity, and SMRs will gain significantly larger shares and reach a combined share of over 90%. This shift aligns well with the conditions outlined in an ambitious scenario for Finland in 2050, emphasizing the increasing importance of sustainable energy sources.

To visually underscore this trajectory, the following bar chart (Figure 20) provides a comparative analysis of waste incineration outputs for the years 2022, 2035, and 2050 under the ambitious scenario. The bars for each respective year showcase the targeted TWh values for waste incineration, offering a clear illustration of the progressive reduction.

Additionally, the same chart incorporates the projections from the previous roadmap, represented in black for 2035 and in red for 2050, providing a comprehensive visual overview of the evolving landscape of waste incineration in Finland's energy production.

This graphical representation serves as a powerful tool to comprehend and communicate the strategic shifts in energy production dynamics, highlighting the strides towards a more sustainable and ambitious future.

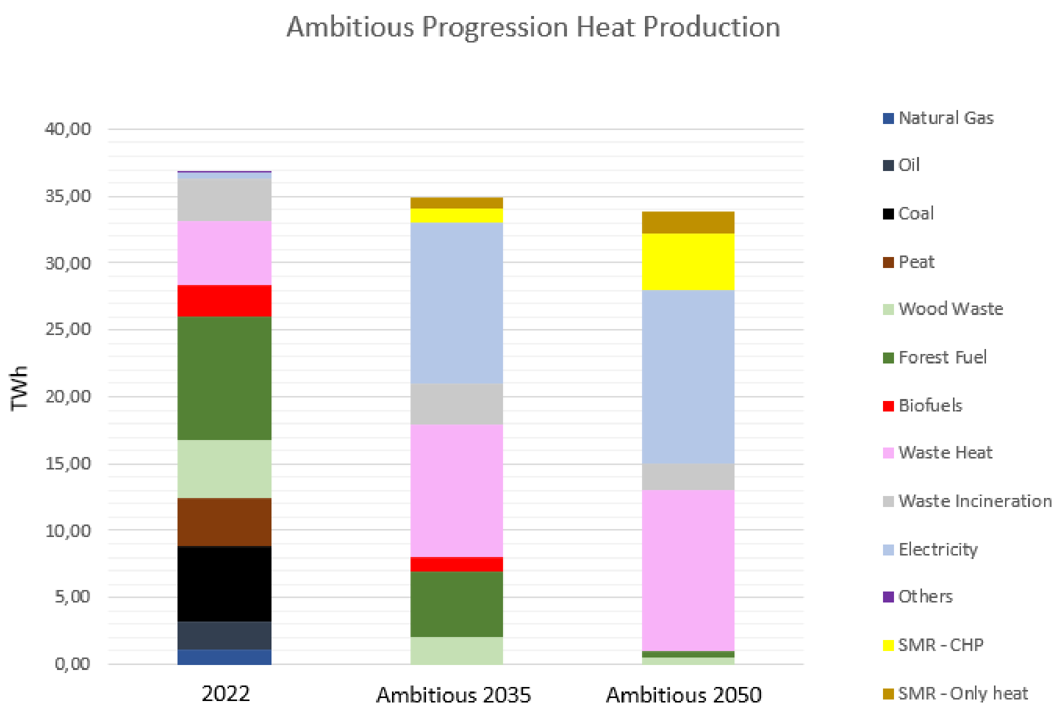

Figure 20: Heat production in ambitious scenario.

6.5 Emissions

The emissions for both power and heat are presented in Figure 21.

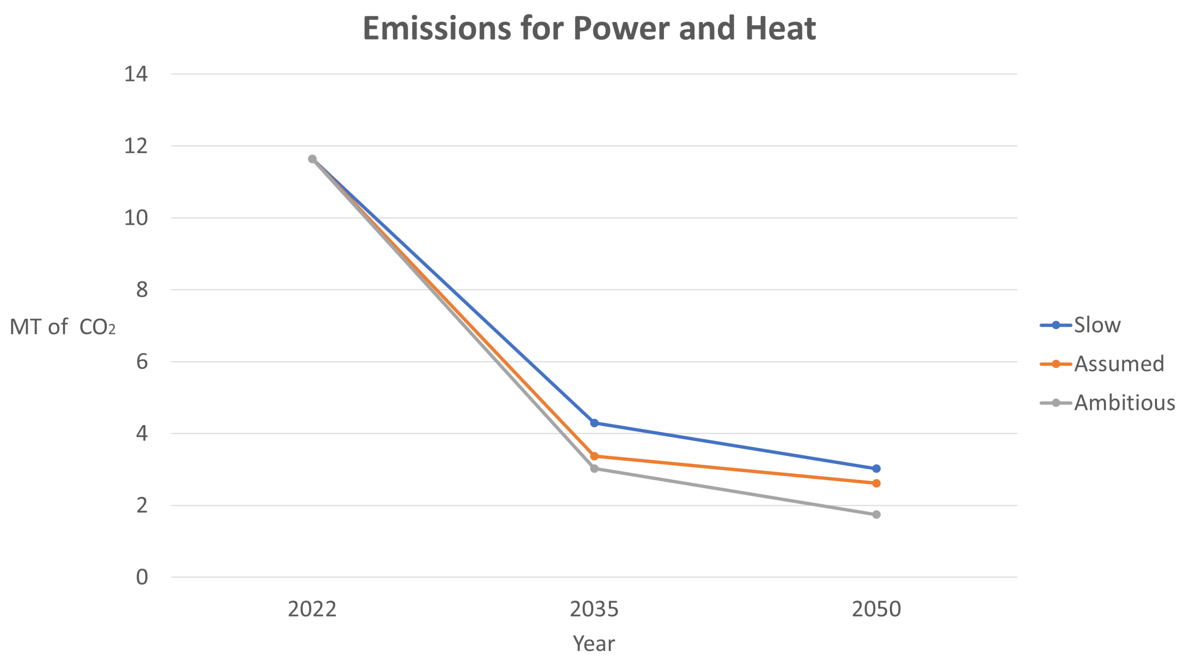

Figure 21: Emissions in the three scenarios.

Emissions are calculated as direct emissions. Therefore only fossil fuels and burnt waste have emissions. Emission factors for renewables are zero, including wood and biomass. The used emission factors can be found in table 2. The factors for each energy source are from Statistics Finland, Production of electricity and heat, energy sources and carbon dioxide emissions Energy method 2021.[61] These factors are multiplied with each energy source production from according scenario. The same method is also used for historical data from 2022.

Table 2: Emission factors for each energy source.[61]

Energy source	Emission factor Power (t/GWh)	Emission factor Heat (t/GWh)
Natural Gas	241,16	228,71
Oil	661,38	324,03
Coal	475,61	367,83
Peat	614,75	463,25
Burnt waste	1630,54	464,37

The emissions reduced remarkably in all of the scenarios, but they are not zero. The roadmap works as a low carbon roadmap, but carbon sinks are needed in order to achieve net-zero emissions. Therefore in the ambitious and assumed scenario use of forest fuels, industrial wood waste and biomass are reduced and replaced with other more sustainable solutions. Emissions from building the infrastructure is not considered in the direct emissions.

7 Comparison of the three scenarios and historical data from 2022

The table 3 below depicts a comparison of the power production of all three scenarios for the years 2035 and 2050 with 2022 as a reference.

Table 3: Comparison in power production: 2022 and updated scenarios.

Power Production [TWh]							
Scenario	**History**	**Slow**	**Assumed**	**Ambitious**	**Slow**	**Assumed**	**Ambitious**
Year	**2022**	**2035**			**2050**		
Oil	0,16	0,00	0,00	0,00	0,00	0,00	0,00
Coal	3,85	0,00	0,00	0,00	0,00	0,00	0,00
Peat	1,72	0,00	0,00	0,00	0,00	0,00	0,00
Import	12,55	5,00	0,00	0,00	0,00	0,00	0,00
Natural Gas	1,07	1,00	0,00	0,00	0,00	0,00	0,00
Hydro	13,34	14,00	14,00	14,00	14,00	14,00	14,00
Wind off-shore	0,15	7,16	18,84	25,84	23,89	68,96	81,66
Wind on-shore	11,56	27,46	40,62	44,37	44,81	81,81	92,07
Solar	0,41	6,00	9,00	15,00	8,00	15,00	20,00
Biofuels	12,14	12,00	15,00	5,00	15,00	15,00	15,00
Waste	0,82	1,00	1,00	1,00	1,00	0,75	0,50
Other	0,00	0,00	0,00	0,00	0,00	5,00	5,00
Nuclear (tot.)	24,35	34,83	38,05	41,28	34,83	44,50	50,95
TOT.	**82,12**	**108,46**	**136,51**	**143,27**	**141,53**	**245,03**	**279,18**

It can be seen that there will be up to 79% increase in power production compared to 2022 mainly due to the electrification of the industry sector for 2035 and up to 241% for 2050.

A phase out of fossil fuels and imports is initiated in all the scenarios and will be reached by 2035 except for the slow scenario where it is delayed. However, there are no imports and no fossil fuels are used in 2050 in any of the scenarios.

A large increase in wind power production can be noticed especially off-shore wind as it as it was not used much in 2022. It is also possible to see the differences in increase in the different scenarios as the share of wind in the slow scenario is half of the ambitious scenario in 2035 and a bit less than half of the production of the assumed scenario in 2050.

Solar power also increases greatly compared to 2022 as it goes from 0,4 TWh to up to 15 TWh in 2035 and 20 TWh in 2050.
Lastly, there is an increase of nuclear production in the three scenarios. While for the slow scenario it increases due to the opening of the Olkiluoto 3 reactors in 2023, the assumed and ambitious scenarios take into account the development of SMRs leading to increase of the nuclear power production up to 51 TWh in 2050.

The table 4 below shows the comparison of the heat production of all three scenarios for the years 2035 and 2050 with 2022 as a reference.

Table 4: Comparison in heat production: 2022 and updated scenarios.

Heat Production [TWh]							
Scenario	**History**	**Slow**	**Assumed**	**Ambitious**	**Slow**	**Assumed**	**Ambitious**
Year	**2022**	**2035**			**2050**		
Oil	2,07	0,00	0,00	0,00	0,00	0,00	0,00
Coal	5,57	0,00	0,00	0,00	0,00	0,00	0,00
Peat	3,69	1,90	0,50	0,00	0,00	0,00	0,00
Natural Gas	1,14	1,00	0,50	0,00	0,00	0,00	0,00
Wood Waste	4,28	4,00	3,00	2,00	3,00	1,70	0,50
Forest Fuel	9,26	8,00	6,00	5,00	7,00	3,50	0,50
Biofuels	2,32	2,00	1,50	1,00	1,50	1,00	0,00
Waste Heat	4,87	7,50	9,00	10,00	9,50	10,00	12,00
Waste Inc.	3,10	3,00	3,00	3,00	3,00	3,00	2,00
Electricity	0,50	9,50	11,00	12,00	11,00	12,00	13,00
Others	0,09	0,00	0,00	0,00	0,00	0,00	0,00
SMR-CHP	0,00	0,00	0,53	1,05	0,00	2,10	4,20
SMR-only heat	0,00	0,00	0,66	0,88	0,00	1,10	1,64
TOT.	**36,90**	**36,90**	**35,68**	**34,93**	**35,00**	**34,40**	**33,85**

It can be seen that the heat production is expected to decrease in all of the three scenarios by up to 5% in 2035 and 8% by 2050 compared to 2022. A large increase in the electricity use for heat production can be noticed as only 0,5 TWh was used in 2022 for up to 13 TWh in 2050, the same can be said for the waste heat which will increase with the expansion of the industry in the next decades which will help phasing-out from fossil fuels.

The ambitious scenario is the only scenario phasing out of fossil fuels by 2035 as peat and natural gas will still be used in the other two scenarios, but a complete phase out of coal is planned by 2035 for all three scenarios.
The increase in waste heat and electricity use in heat production will also help reducing the share of forest fuel and waste wood usage to reduce the carbon emissions caused by those two sectors.

The use of SMRs can also be noticed in the assumed and ambitious scenario by 2035 to reach a heat production of up to 5 TWh in 2050 which will also help reducing the share of forest fuels and wood waste usage. SMRs are not considered in the slow scenario which explain why the forest fuel and wood waste usage is higher than in the other two scenarios.

8 Key findings and conclusion

In this concluding chapter, the key findings and significant changes from the previous roadmap 2019 are highlighted. The forward-looking low-carbon roadmap 2023 for 2035 and 2050 explores various scenarios considering interest rates, carbon prices, climate change effects, and technology developments.
Key assumptions and initiatives, fuelled by valuable insights from diverse European countries' decarbonization strategies, shape the strategic approach for the new roadmap.

In the realm of power, findings suggest that solar production could increase up to 50 times compared to 2022, with wind power emerging as the predominant source, especially through offshore wind farms after 2035. Nuclear production ties closely to combined heat and power SMRs, dependent on the scenario, leading to an overall increase in power production ranging from 73% to 241% compared to 2022. Fossil fuels are phased out entirely, power imports reduced, and the hydrogen economy correlates closely with wind power developments. Furthermore, biofuels usage is significantly decreased by 2050.

For heat, a reduction in forest fuels is achievable, while waste heat experiences substantial increases across all scenarios. Electrification leads to up to 26 times higher heat production compared to 2022, with other changes including a rapid decline in fossil fuels, a slight overall decrease in heat demand, and the presence of SMRs favouring heat production.

Key findings, emerging through a comparative lens, spotlight significant changes in energy sources and production rates, particularly emphasizing the initiation of electrification. Anticipating steep growth in industry, hydrogen economy, and heating, power production rates could potentially soar up to 2,4 times higher than the baseline year.

In terms of emissions, all scenarios in 2050 foresee direct emissions solely from heat and power resulting from waste incineration. The magnitude of these emissions varies, contingent on recycling efforts and efficiency, including the overall assumption for waste production. In the ambitious scenario, there is potential for a remarkable 78% reduction in remaining emissions compared to 2022. As wind power and the hydrogen economy mutually thrive, forest fuels are anticipated to gradually yield to waste heat, electrification, and SMRs.

Finally, it is crucial to emphasise that the outcomes of each scenario's low-carbon roadmap strictly correlate on the variability of identified general assumptions. While the effects on each energy source have been meticulously studied, uncertainties stemming from unforeseeable events and developmental factors up to the year 2050 are evident in several instances, resulting in substantial deviations between scenario outcomes.
Despite these uncertainties, the significance of this report for Finland's low-carbon roadmap in 2023 lies in its role in steering decisions towards a low-carbon future, encompassing both electricity and heat production. A final recommendation underscores the importance of regularly updating the roadmap every two to three years, relying on empirical reassessment of assumptions for each scenario.

List of Figures

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A Appendix

	Belgium [BE]	France [FR]	Germany [GE]	Italy [IT]
Natural gas	28,6%	6,4%	17,7%	53,1%
Oil	0,2%	1,0%	0,8%	2,8%
Coal	0,1%	1,0%	27,5%	0%
Peat	0%	0%	0%	0%
Hydro	4,7%	11,2%	3,4%	17,6%
Wind off-shore	0%	0%	0%	0%
Wind on-shore	1,8%	6,9%	21,3%	7,4%
Solar	1,7%	2,8%	8,3%	9,1%
Biofuels	2,8%	0,8%	1,8%	1,6%
Waste	1,5%	0,4%	1,1%	0,9%
Geothermal	0%	0%	0%	0%
Nuclear	58,7%	68,4%	11,6%	0%
Other	0%	1,1%	6,6%	7,4%

Table 5: Summary of electricity production percentages of each country analysed for 2021 (imports not considered).

	Belgium [BE]	France [FR]	Germany [GE]	Italy [IT]
Import	24,8%	0%	0%	8,7%
Natural gas	0%	4,6%	0,2%	5,0%
Oil	0%	0%	0%	0%
Coal	0%	0,4%	0%	0%
Peat	0%	0%	0%	0%
Hydro	0%	9,9%	2,1%	7,5%
Wind off-shore	22,8%	2,3%	24,8%	9,2%
Wind on-shore	16,0%	24,4%	30,4%	18,8%
Solar	31,5%	17,9%	34,9%	48,5%
Biofuels	0%	1,6%	1,8%	0%
Waste	0%	0%	0%	0%
Geothermal	4,8%	0%	0%	0%
Nuclear	0%	39,0%	0%	0%
Other	0,3%	0%	5,9% (Hydrogen)	2,3%

Table 6: Summary of electricity production percentages of each country analysed for 2050.

	Belgium [BE]	France [FR]	Germany [GE]	Italy [IT]
Natural gas	72,6%	37,9%	50,2%	70,5%
Oil	0,2%	4,9%	1,3%	10,9%
Coal	0%	2,4%	22,1%	0%
Peat	0%	0%	0%	0%
Industrial wood waste	0%	0%	0%	0%
Forest fuel	0%	0%	0%	0%
Biofuels	0%	0%	3,1%	0%
Waste	10,1%	9,9%	9,4%	2,4%
Synthetic fuels	0%	0%	0%	0%
Electricity	17,2%	44,9%	13,9%	16,2%
Geothermal	0%	0%	0%	0%
Nuclear	0%	0%	0%	0%
Other	0%	0%	0%	0%

Table 7: Summary of heat production percentages of each country analysed for 2021.

	Belgium [BE]	France [FR]	Germany [GE]	Italy [IT]
Natural gas	0%	0%	0%	1,3%
Oil	0%	0%	0%	0%
Coal	0%	0%	0%	0%
Peat	0%	0%	0%	0%
Industrial wood waste	0%	0%	0%	9,0%
Forest fuel	0%	0%	0%	0%
Biofuels	9,0%	9,6%	7,2%	2,0%
Waste	0%	6,2%	3,3%	2,0%
Synthetic fuels	9,0%	0%	0%	0%
Electricity	81,0%	77,2%	41,8%	26,0%
Geothermal	0%	3,7%	11,1%	11,0%
Nuclear	0%	0%	0%	0%
Other	1,0% (gas H_2)	3,4% (biomass)	7,8% (solar) 22,2% (hydrogen) 6,5% (industrial waste heat)	42,7% (biomass) 6,0% (solar)

Table 8: Summary of heat production percentages of each country analysed for 2050.