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REPORT ON THE TRANSITION TO NON-COMBUSTION-BASED AND CARBON-NEGATIVE DISTRICT HEATING

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TAMPEREEN ENERGIA

Foreword

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1 Introduction

This report examines non-combustion-based and carbon-negative city heating from the viewpoint of Tampereen Energia. We published the first such report on 1 September 2021 and published an update in 2023. The first report was prepared at the request of the Tampere City Council. At the beginning of the work, we noticed that the complex questions involved needed to be opened up fully to have value. We observed that there was little publicly available information of the type needed to form a national level vision for heating. Our second observation was that district heating has been such an obvious and well-functioning part of society in Finland for so long that it is not actually very well understood.

At the beginning of the work, we asked openly whether district heating systems are needed at all or whether there might be a new winning technology for heating in Finland. This series of publications thus has a rare starting point and analyses the energy system as a whole from the perspective of heating. The report's starting point and purpose are of general benefit, even though the topic is viewed in the light of information gathered from Tampereen Energia's own activities. The report is suitable as support for research and familiarisation in different organisations. We believe and hope that the report has in part improved awareness of Finland's strengths and the applicability and limitations of new heating technologies. On the other hand, the rapid change in the operating environment will require the information to be updated regularly. The aim of this report is, in addition to being an update, to deepen knowledge of the interrelationships in the district heating system, the electricity system and the land use sector.

By 2027, Tampereen Energia will reduce its fossil emissions by about 90% compared to the level in 2010. They will continue to reduce emissions, but the effectiveness of the remaining measures will decrease year by year, because the potential for reductions is smaller. For the last tonnes, the risk of wasting resources and partial-optimisation grows. It is therefore timely to examine what kind of plan is cost-effective and generates real net emission reductions at the final stage of the project.

In this report, we consider the role of district heating companies in society's journey towards a low carbon future, with Finland's largest sources of fossil emissions already outside energy production. After emission reductions, district heating companies' relationship with climate policy comes from their ability to help other sectors, such as transport, in achieving their emission reduction targets. In other words, we are talking about the sector coupling capability of the district heating system and the opportunities for a positive carbon handprint. (A carbon handprint refers to beneficial environmental impacts, rather than the negative environmental impact of a carbon footprint.)

In this report, we respond to the basic trilemma in the energy sector, i.e. the triple problem of energy and its environmental impacts, affordability and security of supply. Responsible city heating is not only as harmless as possible, but it is also something that people can afford and whose availability can be trusted in all situations. This report is part of the ongoing work to find the best solutions to this energy trilemma both in Tampere and nationally.

Heating technologies are developing and competition is also tightening. In Finland and Sweden, there are several cities where district heating has fared surprisingly poorly in competition. The background to these failures usually involves delayed investments in renewable energy and mistakes in district heating pricing, in which the competitive situation was not recognised in time. However, district heating systems built over generations could have a very special capability to support the green transition. In this report, we also aim to describe the unique opportunities that district heating systems can provide.

1.1 Summary of non-combustion in heating

Covering peak consumption situations is the most important challenge in heating. Current alternatives to district heating deal with peak consumption situations by relying on the electricity system. In practice, the question of whether a non-combustion-based heating system is worthwhile largely comes down to how peak consumption management differs between the electricity system and the district heating system, given that both are already very low-emission. In this report, it is essential to emphasise that heat produced used electricity cannot classed as non-combustion if the electricity itself is produced using combustion.

Many waste heat and ground-source heat pumps require a heat pump to capture the heat. This consumes a significant amount of electricity and thus makes the pumps and the heat they produce dependent on the electricity system. Non-combustion-based electricity production methods are variable electricity production (wind and solar), geothermal energy in volcanic areas, hydropower and nuclear power. If unprofitable technologies or prototypes are excluded, there are no other non-combustion methods of electricity production. All non-combustion electricity production technologies are very capital-intensive compared to combustion.

The problem of short utilisation time and large committed capital is accentuated in Finland, where the heating consumption peak is very high and peak consumption situations are typically low-wind and sunless. Significant additional construction of hydropower is not possible in Finland, and it does not make sense to build more nuclear power plants to handle just a few weeks of peak consumption. Options for completely non-combustion electricity peak consumption management are scarce.

What remains is energy storage. Energy can be stored for later use either as electricity or heat, or using an energy carrier such as hydrogen. To make construction of storage more worthwhile than construction of production, construction of storage must be inexpensive. Although electricity storage prices have fallen sharply, they are still extremely expensive for storing large amounts of energy. Pumped-storage plants could serve as a partial solution in Finland, but even then, their scale does not extend beyond weekly storage. For example, the upper reservoir of the Ailangantunturi pumped-storage power plant discharges in about 8 hours. Storing energy as heat is fortunately significantly cheaper. As will be discussed later in the report, large-scale district heating storage is a key technology in a non-combustion energy system.

An essential question is also whether we truly want a non-combustion energy system or whether this term is used as a synonym for a system without fossil fuels and bioenergy. For example, using hydrogen as a fuel would also be possible in energy production. Heat pumps are seen as a non-combustion solution, but without week-long flexibility they only outsource peak production combustion to the electricity system. Carbon dioxide capture from incineration of non-recyclable waste or bioenergy would enable the heating system to be carbon-negative. Carbon-negativity has more impact in climate work and is also cheaper to achieve than non-combustion.

1.2 Overview of carbon-negativity in heating

Building a non-combustion heating system is more expensive than building a carbon-negative heating system. The additional environmental benefits of a non-combustion heating system would therefore have to be worth the additional cost and larger net emissions.

Carbon-negativity is achieved when more carbon dioxide is removed from the atmosphere than is emitted into it. In the context of heating, this means using technology to capture carbon dioxide from bioenergy. Capture is needed because, despite emission reductions, residual emissions will remain. Achieving net zero alone is not sufficient to avoid the catastrophic impacts of climate warming; large-scale and long-term removals are the only way to gradually bring the world's temperature back within desired limits.

[1] kemijoki-oy-yleisotilaisuus-kemijarvi-192025.pdf

In this report, we examine a realistic path to technical carbon sequestration. Carbon dioxide capture linked to bioenergy could be Finland's competitive advantage, but current policy does not support this direction. Carbon dioxide utilisation projects are progressing faster than storage projects because they have a clearer business model. A breakthrough in capture technology would require ambitious national targets, support mechanisms and measures to build infrastructure. We see potential particularly in carbon dioxide utilisation projects, because value is naturally created through the use of waste heat, and the political risk to the core business is smaller.

Carbon dioxide capture is carbon-negative only if the captured carbon is permanently stored. From the perspective of a district heating company, it increases the carbon handprint of the district heating system if carbon dioxide is utilised in products in another sector, for example as transport fuel. The carbon handprint describes achieved positive climate impacts. In this report, carbon dioxide capture in the district heating system is viewed as a positive climate action regardless of whether the carbon is stored or utilized.

From the perspective of sustainability, the report examines, among other things, the impact of bioenergy on natural carbon sinks and the sustainability of different bioenergy sources relative to each other. Answering these sustainability questions correctly is essential in optimising the whole. If stopping bioenergy production is not actually an effective environmental measure, we will end up only slowing down climate change mitigation and raising the cost of heating.

If the capability of forests to capture carbon dioxide is not utilised in climate work, an important enabler of carbon-negativity will be lost. According to the scenarios of the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide capture from bioenergy has a central role in achieving the goals of the Paris Agreement. It would also be a special national strength and competitive advantage for Finland in climate work in Europe.

1.3 Research questions

According to the original purpose of this report, we should clarify with which combination of non-combustion and carbon-negative solutions district heating production can be implemented in the most cost-effective, secure and low-emission way. This question is approached using the following research questions:

TK1: Can Finland's electricity system be non-combustion by 2040?

TK2: What types of technologies exist for non-combustion and carbon-negative heat production?

TK3: What kind of heating system that combines different technologies could minimise emissions and costs?

TK4: What conclusions can be drawn from examination of different scenarios in the national and EU-wide regulatory and market environment?

Research question **1** is answered in chapters **2.2** and **3**. To answer it, we first respond to the following sub-questions:

a. What is the power balance in 2040?
b. What technologies exist for non-combustion power management?
c. How does city heating through the electricity system affect Finland's electricity system?

Research question 2 is answered in chapters 4 and 5. To answer it, we first respond to the following sub-questions:

a. What should the role of bioenergy in the energy system be?
b. What are the challenges and opportunities with different non-combustion and carbon-negative technologies?

Research question **3** is answered in chapter **6**.

Research question **4** is answered in chapter **7**.

1.4 Starting assumptions

The dimensioning example under examination is a cold and low-wind week. The heating system is built around how to ensure heating for the whole city during the coldest week of the year. In Tampere, there are more than ten heating plants to manage the district heating power problem, which may be needed only for a week or two per year, since typically the duration of the peak load period is of this order. The plants are kept operationally ready even though they are almost always idle. District heating's readiness for demand and price peaks is a structural part of operations, in procurement contracts, on-call duties, backup plants and storage. The harshest cold spell may be short, but it is the core question of the heating challenge, which is always answered first.

Heating demand will decrease as we move towards the 2040s. The most important factors in the change in demand are building energy efficiency, city population growth and climate change. New residential buildings are twice as energy efficient as those from the 1990s. Tampere's population is growing at a rate of two percent per year, but the improvement in building stock energy efficiency compensates for the increase in energy consumption caused by growth. At the same time, a warming climate reduces the need for heating. For example, in Tampere, the Heating Degree Days index has decreased by about 13°Cday per year during the 2000s. Based on observation, the required power will decrease somewhat more slowly than the required energy. In addition, district heating demand is affected by market share, if some buildings switch to building-specific solutions. The smaller need for district heating has been taken into account in the scenarios according to the best forecasts available.

The target year in the scenarios is 2040. The City of Tampere has a carbon neutrality target for 2030, Finland for 2035 and the EU for 2050. For Tampere's emission target, it is planned that some of the residual emissions will be compensated, whereas Finland's and the EU's targets mean net zero greenhouse gases for the whole area including carbon sinks. In July 2025, the European Commission published a proposal that European net emissions must be reduced by 90% compared to 1990 levels by 2040 as an interim step towards climate neutrality. At present, EU climate policy has dropped in priority because the Union has had to focus on trade policy and defence, and some EU countries have supported easing climate targets at the latest summit. We nevertheless assume that in the 2030s political guidance will lead to investments and that 2040 is still a relevant timeframe, and that the changed operating environment will support the achievement of climate targets set by companies.

The harmful impacts of energy production are simplified to emission impacts. Energy production has many kinds of impacts on the environment and society. The harms of fossil fuels – not only to the climate, but also to biodiversity or human rights – are greater than those of sustainably sourced renewable fuels. We therefore consider that focusing on emission impacts does not distort the overall picture of negative impacts too much, but it does improve the clarity of the report significantly. Other important responsibility perspectives are included to a small degree, for example when analysing the land use sector. The reader can familiarise themselves with other perspectives in our sustainability reporting, which is in line with the Corporate Sustainability Reporting Directive (CSRD).

The scenarios are based on current technology. The aim of the work is not to create an optimised development path to 2040, but to increase the reader's understanding of current challenges and realistic alternatives for the transition according to the best current knowledge. Using overly speculative technology in the scenarios would not support this. Our plans will be updated as technologies develop.

[2] EU-johtajat asettivat uudelle ilmastotavoitteelle kolme ehtoa | HS.fi

2 District heating as part of the energy system

The district heating system is interconnected with society in many ways. When we think of the energy trilemma, finding the best solutions is challenging, and energy policy does not always make the task easier. The war in Ukraine and Donald Trump's rise to power in the United States have influenced climate policy by emphasising the themes of security and competitiveness. Climate change and biodiversity loss, however, are still problems that are getting more serious. In this political cross-current, we emphasise the need for a comprehensive vision.

The greatest challenge in heating cities is the management of peak consumption situations. Non-combustion-based energy is usually easily available. Over the course of a year, steady demand would be easy to cover. In reality, heating demand increases more than tenfold from summer to peak winter frost, whereas electricity consumption only doubles. Thus, dealing with variation within the year, month and even day is a central part of the problem, and heating cities during peak frost is a particularly difficult challenge for the electricity system.

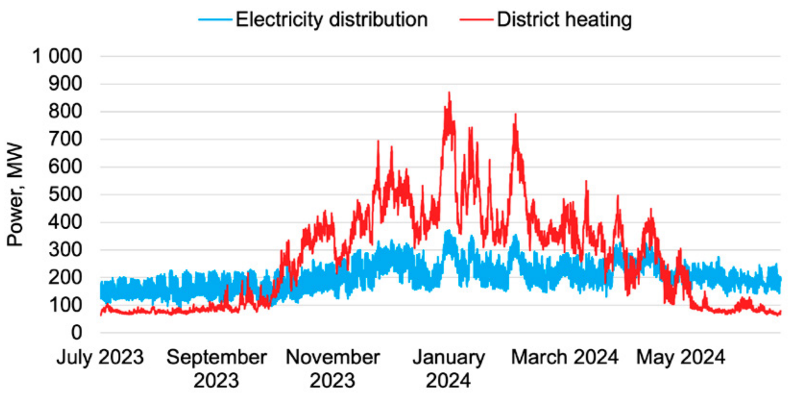


Figure 1. Hourly electricity and district heating demand in Tampere in winter 2023–2024.

The district heating system is built around the issue of how to ensure heating for the whole city during the coldest week. The city heating must function at the coldest moment without electric boilers, even if the largest power plant fails. Managing extreme situations in the electricity system is closely connected to this, because heating methods that compete with district heating almost invariably take the required additional power from the electricity system during the harshest frost. Non-combustion should not be promoted through partial-optimisation, and preventing this requires examining the electricity and heating systems together at least at an hourly level. If the power problem is simply passed on to the electricity system, heating emissions and costs increase and reliability deteriorates.

When the aim is to participate effectively and cost-efficiently in climate action, net emission reduction is a decisive way to do it. Efforts must be directed to solutions that lead to net zero emissions for the whole energy system. With partial-optimisation, this does not happen. If limited resources and expertise are targeted incorrectly, reaching the emission target will be slowed and Finland's competitiveness and opportunities for success will be weakened.

2.1 The Tampere district heating system

By 2027, fossil emissions from Tampere's energy production will have decreased by about 90% compared to 2010. Since 2010, Tampere has made determined investments to reduce fossil emissions and heat production has completely changed. At present, the Tampere heating system rests on three pillars: electric boilers, biofuels and industrial waste heat. Peak production, which accounts for 5–10% of the annual heating energy, is produced with fossil fuels and biogas. In 2025, 40% of the gas fuels used for heat production will be biogas. The use of biogas in heat production varies annually depending on market conditions and availability.

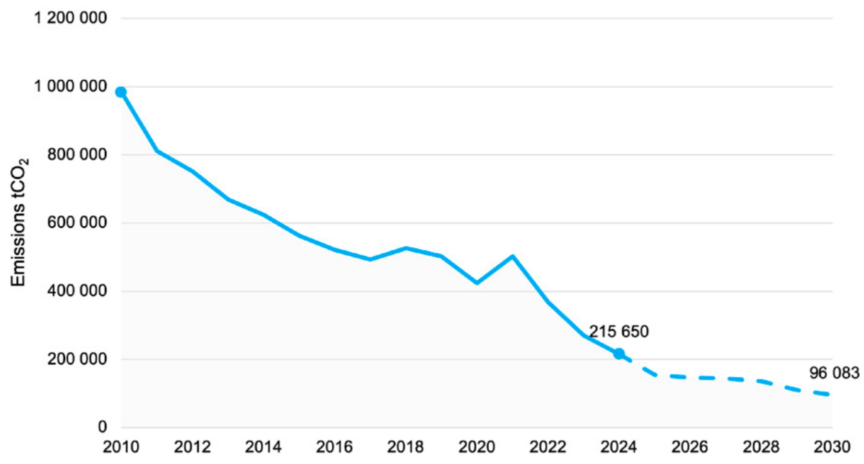


Figure 2. Actual and forecast emissions from Tampereen Energia's energy production.

2.1.1 What has been done since the 2023 report

Since our previous report, electricity production from the Olkiluoto 3 nuclear power plant has stabilised and wind power has grown to become the second largest form electricity production in Finland, when measured by annual in terms of annual energy output. In Tampere, the non-combustion heat production capacity was expanded in early 2025 with the addition of an industrial-scale heat pump in Naistenlahti, and in autumn 2025 with new electric boilers and district heating storage.

The new heat pump utilises excess heat from the power plant's flue gases, and the electric boilers use wind-power-based electricity. This is ensured in the company's control rooms thanks to minute-level optimisation capability. Tampereen Energia not only obtains Guarantees of Origin for the electricity it uses, but it also schedules its consumption on the electricity market so that it does not consume electricity at prices that rely on fossil fuels for electricity production.

2.1.2 The pillars of the Tampere district heating system in 2027

The large regional market share of district heating means that focusing only on a certain customer segment (environmentally conscious, price-conscious or quality-conscious) does not work, because it excludes a significant part of current customers. District heating customers are typically long-term and economically significant. A centralised heating system must be, in the longer term, better than alternatives in all the most important aspects, so that the business does not shrink. This is naturally a difficult challenge, but the strengths of district heating make it possible.

District heating production in Finland is already low-emission. Fossil carbon dioxide emissions from heat production arise almost exclusively from solving the power problem, i.e. from peak production. Figure 3 shows a simplified production overview of district heating in 2027.

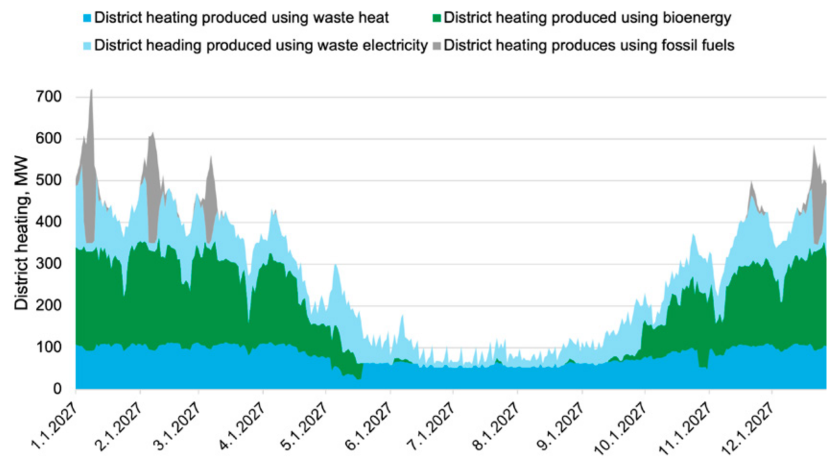


Figure 3. Tampereen Energia's district heating production structure in 2027 is based on investments that have already been decided. In this graph, district heating produced using waste heat includes waste incineration, flue gas scrubbers and industrial waste heat sources. District heating produced using surplus electricity includes electric boilers and heat pumps. Fossil district heating, on the other hand, is natural gas. Some of the peak production requirements can be purchased as biogas.

Pillar 1: Waste heat

Related district heating strength: **sector coupling capability**

The large potential of waste heat in the district heating network is based above all on the increase in hydrogen production and data centres. If even a fraction of the ideas of project developers are realised alongside district heating networks, in future heating for Finnish cities will be interlinked with data and hydrogen production. This could be called a new era of combined production. Previously, larger cities in Finland were heated using combined heat and power (CHP), which can also be described as waste heat from electricity production.

In Tampere, the first year-round industrial waste heat source was the Nokia data centre, and waste heat from this has been utilised since 2021. The amount of recovered waste heat is growing continuously. In Pirkanmaa, several other data centre projects are planned, and in future it would be possible to recover heat from these into the district heating network.

Hydrogen sector project developers are also very active in Tampere. According to current plans, carbon dioxide from Tammervoima's flue gases will be utilised in synthetic fuel production. Based on the current timetable, the waste heat from this synthetic fuel plant will be fed into the district heating network from 2028 onwards. Interest has also been shown in carbon dioxide from the Naistenlahti plant. Waste heat is discussed in more detail in chapter 5.3.

Pillar 2: Surplus wind power

Related district heating strength:
precise minute-level optimisation of electricity use

Finland's wind power capacity has grown rapidly, but consumption has not increased correspondingly. During windy periods, the market price of electricity can fall to zero or become negative, and some turbines must be stopped for economic reasons. This unused wind power production can be called surplus electricity.

District heating companies with electric boilers have the ability to utilise surplus electricity. Electric boilers can produce heat either for direct use the district heating network or store it in thermal batteries. This is possible because the district heating systems are connected to several different forms of renewable production, which can be adjusted flexibly according to the situation in the electricity system. The current state of the electricity system is discussed in more detail in chapter 2.2, electric boilers in chapter 5.2 and heat storage in chapter 5.1.

Pillar 3: Bioenergy

Related district heating strength: **independence from weather, price stability**

Biopower plants even out the variation of weather-dependent energy sources. Unlike wind and solar power, bioenergy-based production is not dependent on weather or time of day, but is available when heat is most needed. In Finland, biofuels are primarily side streams of the forest industry, such as logging residues, sawdust and bark, as well as forest chips produced from small-diameter wood unsuitable for further processing.

In the energy system, there are situations where the use of bioenergy causes fewer negative environmental impacts than the use of electricity, and vice versa. In shortage situations, electricity production can be momentarily very polluting, even if average emissions are small on an annual basis. In such cases it is important to avoid electricity use and utilise biofuels. Electricity is best used for heating in situations when there is surplus wind power. Surplus situations may last for days or only hours. A centralised heating system that can combine electricity and bioenergy flexibly according to the state of the electricity system minimises the environmental harm of both energy sources.

Bioenergy has replaced peat in Tampereen Energia's production palette, which has been the fastest implementable way to reduce fossil emissions in energy production. The sustainability of bioenergy is discussed in more detail in chapter 4.

Pillar 4: Good management of peak load situations

A related special strength of district heating: **power management does not rely on the electricity system and has high efficiency**

When managing peak consumption, balancing the points of the energy trilemma is essential. Combining low emissions with reasonable price and security of supply is very challenging when the power situation tightens, when supply disruptions would have particularly serious consequences and the price of energy can momentarily be out of control.

When the price of electricity is high, peak and reserve power in the district heating system is produced mainly using gas. In Tampere, this accounts for about 5–10% of annual heating energy. Large thermal batteries and renewable gases are gradually reducing the need for fossil gas in covering peak heating demand. In 2025, fossil natural gas was partly replaced with biogas. Biogas is discussed further in chapter 5.11. Oil is also an important reserve fuel for managing the most extreme situations thanks to its storability, which is a challenge with other fuels, for example, with wood chips.

The scale of a city-wide heating system is what enables it to maintain reserve power. However, ensuring power management for small sites with stand-alone boilers is expensive, which leads independent heating solutions to rely on the electricity system to cover peak demand.

Energy storage is a notable strength of district heating systems, when it comes to solving power problems. Storing energy as heat is tens of times cheaper than in electricity batteries. District heating storage systems are now being built rapidly across Finland.

In the harshest winter frost periods, the electricity system relies on fossil condensing electric power plants, whose efficiency remains around 40% because the heat generated in condensing electricity production cannot be recovered. One of the strengths of the combined heat and power and boilers used in district heating systems in power management is their very high efficiency, which is about 90%.

District heating system heat boilers produce heat precisely when the electricity system is most heavily loaded. If all heat power were produced with electricity during peak consumption, the electricity transmission grid and peak production capacity would have to be dimensioned for the extremely large power needed only for a few days per year. This would increase not only costs but also increase the negative environmental impact through construction lifecycle emissions.

It is worth noting that the special strengths and impact of the district heating system in climate work are based on converting a large volume of heat production centrally to make it emission-free. These strengths are partly opposed to factors in the E-number – this defines the sustainability of energy use in buildings, in which emission reductions are sought through, for example, building-specific production. On the other hand, the calculation does not recognize the emission-free nature of local district heating or the system-level efficiency challenges if peak consumption is significantly transferred to the electricity system. The challenges with the E-number calculation are discussed in more detail in Chapter 5.11.

2.2 Electricity system

In this chapter we answer research question 1: **can Finland's electricity system be non-combustion by 2040.** First, we examine two sub-questions: what is the power balance in 2040 and what technologies exist for non-combustion power management in the electricity system. Based on our analysis, we conclude that during a calm, low-wind week the electricity system will not be non-combustion, and therefore a non-combustion heating system cannot rely on electricity use during severe frost.

The expansion of wind power, the start-up of Olkiluoto 3, the shutdown of coal power and the end of Russian imports have reshaped the electricity system over the past five years. Therefore, it is important to study the dynamic phenomena of the electricity system from the recent past. Five-year-old data is inevitably outdated. Figure 4 shows the changes in Finland's electricity procurement from 2021–2025. Thanks to increased nuclear and wind power, there is no shortage of energy, and on average there is more electricity available than needed. The amount of energy produced in the Finnish electricity system has increased, while at the same time the flexibility of production has decreased.

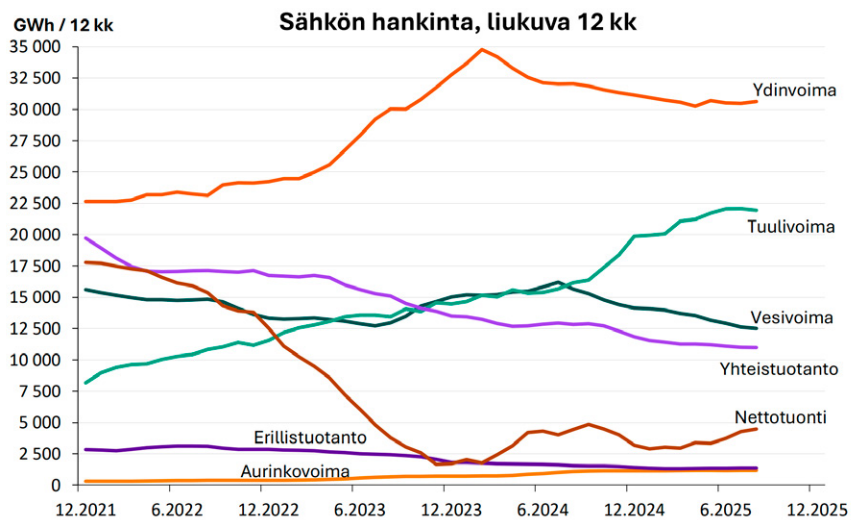


Figure 4. Changes in Finnish electricity procurement from 2021–2025.[3]
From top to bottom: Nuclear power, Wind power, Hydroelectric power, Co-generation, Net import, Stand-alone generation, Solar power.

Between 2021 and 2025 the availability of electricity power in peak consumption situations has changed as follows:

- Imported from Russia -1300 MW
- Combustion-based electricity production - 871 MW
- Olkiluoto 3 +1600 MW
- Aurora Line + 700 MW
- Wind power + 397 MW
- **Total** **+ 526 MW**

In total, electrical power availability has increased by about 526 MW compared to 2021. One of the major structural changes is that flexible production power has decreased and been replaced by nuclear and wind power. This has increased price variation.

The nominal capacity of wind power rose between 1 January 2021 and 9 July 2025 from 2 268 MW to 8 885 MW. This has increased the calculated wind power capacity in peak consumption situations by 397 MW, since for wind power a calculated 6% usability is used in extreme consumption situations. In Finland, extremely cold weather is typically calm. A six percent design capacity is quite cautious, but even lower usability occurs all the time. In the winter peak of 2024, about 25% of nominal capacity was available.

Combustion-based electricity production has decreased at an accelerating pace since 2010. Especially after the energy crisis in 2023–2025 plants have been closed quickly and permanently, for example Salmisaari and Suomenoja . We have assessed the amount of electricity production on the market from actual maximum peak output read from hourly data. Reasoning based on realised data is sensitive to exceptional electricity market situations in each year, but at least it is firmly anchored in reality. Based on actual data, combustion-based electricity production has decreased by -871 MW during the review period. We see that in the future plant closures will continue.

[3] Sähkön kuukausitilasto - Energiateollisuus

[4] Helenin viimeinen kivihiilivoimala sammuu Salmisaaressa päättäen hiilen aikakauden

[5] Fortum lopettaa hiilen käytön kaukolämmöntuotannossa etuajassa

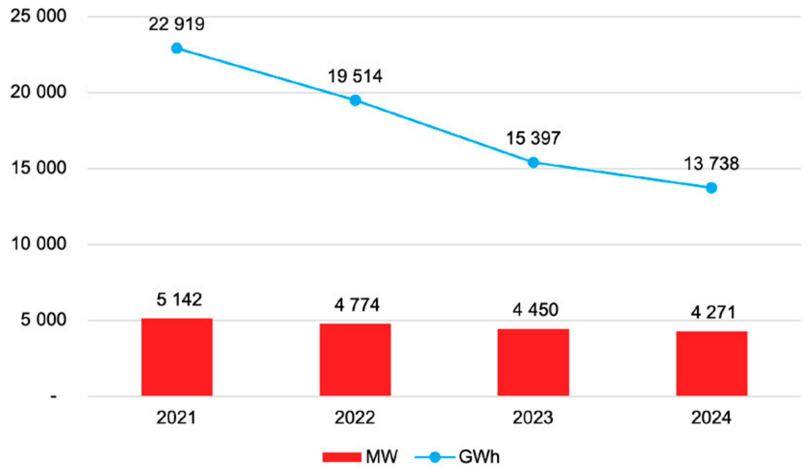


Figure 5. Peak hourly power (MW) and annual production (GWh) of combustion-based electricity production (industry CHP + district heating CHP + condensing power generation). [6]

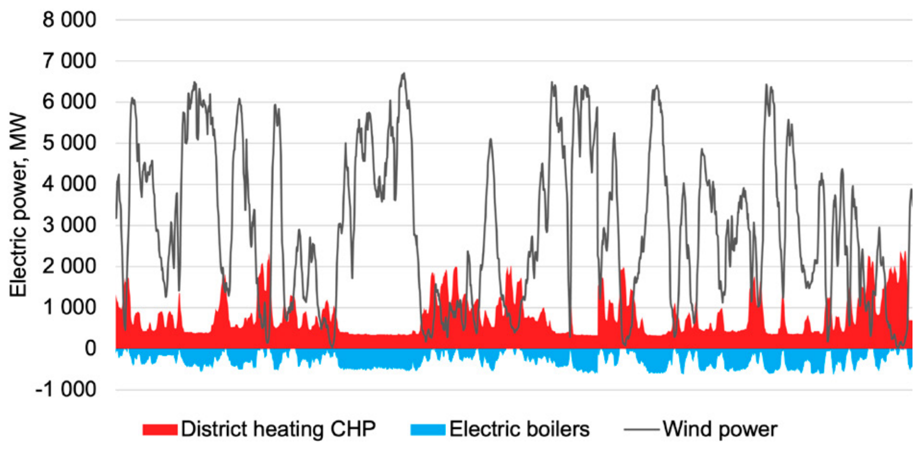


Figure 6. Fluctuation in electric boilers and district heating CHP according to wind conditions 12/2024-02/2025. Source: Energiateollisuus/Finnish Energy hourly data and Fingrid electric boiler data.

District heating systems are critical sources of peak and reserve power, especially when there are disturbances in electricity imports or nuclear plants. In addition, district heating companies also balance the peak and negative prices of electricity. In Juha Teirilä's analysis, in a mild winter 2024–2025 other flexibility remained small. District heating companies quickly increase production when prices rise, or use electric boilers when there is surplus wind power. Industry and households are still not very flexible. The fluctuation of district heating electricity consumption and production depending on wind speed is shown in Figure 6.

The previous period of frost that was demanding for the electricity system was in January 2024. An examination of the situation provides concrete details about the power problems in the electricity system. At that time, approximately 500 MW more variable CHP production was still in use than at present. The situation in the electricity system on the day of peak demand is presented in Figure 7.

[6] Sähkön tuntidata - Energiateollisuus

[7] Sähkömarkkinan ääritilanteiden anatomia – kuka joustaa ja kuinka paljon? - Reilua Energiaa

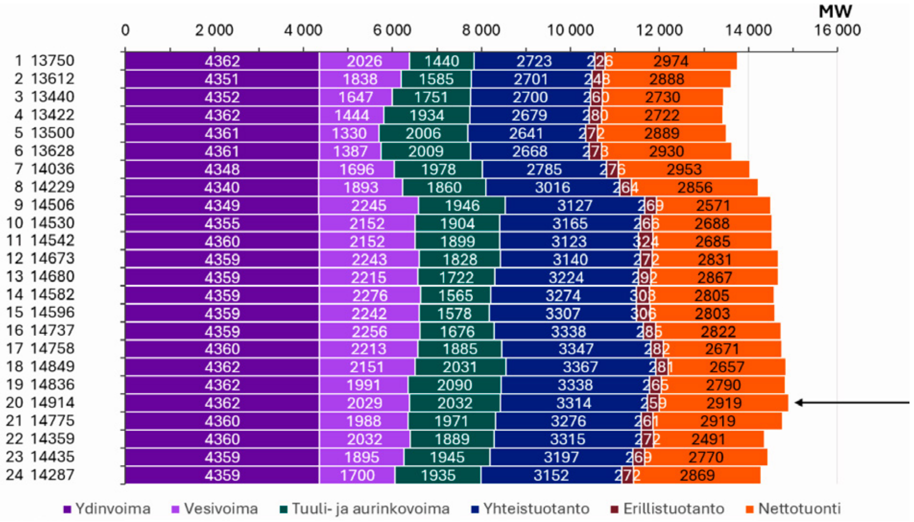


Figure 7. Electricity purchase by the hour on January 3, 2024. The sum of the fees is the consumption in that hour.[8] From left to right: Nuclear power, Hydroelectric power, Wind and solar power, Co-generation, Stand-alone generation, Net import.

The period was not windless, but it was low-wind, which is typical of frosty periods in Finland. During severe frosts, nuclear power and industrial electricity production operate at full capacity. Finnish hydropower production can be adjusted within a day, but the amount of capacity available is not enough to manage the power problem. The remaining adjustments required were made by utilizing district heating cogeneration plants and increased imports, especially from Estonia.

When examining the development of the electricity market and its effects on heating systems, two key observations emerge. First, for most of the year, surplus wind power production, i.e. surplus electricity, is available and it is worth utilizing it flexibly for district heating production. Second, cold, windless periods are problematic. In these cases, district heating CHP plants play an essential role in maintaining the power balance of the electricity system. Since there is sometimes a shortage of electricity and sometimes an excess of production, flexibility is key when utilizing electricity in heating systems. The widespread use of fully electrified heating systems increases inelastic demand for electricity, especially in winter, and concerns about the adequacy of electricity during periods of calm frost are growing in Finland and neighbouring countries.

2.2.1 The Nordic electricity market model

The amount of flexible electrical power in the system has decreased and political concern about the situation has grown. Support mechanisms have been proposed as a solution, and their strengths and weaknesses require a review of the Nordic energy market model. Here we present only a summary; a more detailed description can be found in appendix 9.1.

In the Nordic energy-only electricity market model, payment is made only for the energy delivered. The strength of the energy-only model is the low overall cost of electricity, since customers do not have to pay for the overcapacity that arises in other market models. The main alternative to the energy-only model would be to also pay for power, in which case we would speak of a capacity market. In a capacity market, a power plant receives payment not only for the electricity it produces but also for its readiness to produce electricity. A capacity market can centrally ensure sufficient availability of electricity power. The strength of a capacity market is therefore the possibility to guarantee high security of supply even in exceptional circumstances. However, a capacity market has the weaknesses of a centrally directed system. The central planner typically procures too much electrical power, which extends the lifetime of the oldest, most polluting power plants longer than would really be necessary. In addition, capacity payments must also be made to plants that would have remained in production even without the capacity market. This increases the average cost of electricity. For this reason, the energy-only model used in Finland since the late 1990s has mostly been considered better than other alternatives.

The weakness of the energy-only model is its built-in tendency towards power shortages. This tendency is corrected only if the system has a lot of de-

[8] Sähkötilastot - Energiateollisuus

mand-side flexibility and the price of electricity is regularly in the thousands of euros per megawatt hour. In theory, the model is nationally optimal. It activates creativity on both the production and demand sides, so that expensive power plants do not need to be kept in reserve for rare consumption peaks.

However, this model requires political decision-makers to have the courage to tolerate periods of high electricity prices. The energy crisis showed that political tolerance for these periodic high electricity prices is low. Producers who built emission-free energy production were penalised with a windfall tax. During the crisis, it was also observed that if the system drifts into a power shortage, we are prepared to give energy producers generous subsidies, for example the Iberian price cap for natural gas[9] and the construction of fossil peak power plants in Ireland.[10]

If, on one the one hand, energy companies risk being penalised for investments that prevent power shortages, and on the other hand, subsidies are handed out for investments in emergency situations, it is very difficult to justify investments to prevent power shortages as profitable business.

Investments in peak production therefore involve risks that are too large for operators to accept. State-supported solutions have been sought to manage risks and secure investments through capacity market studies[11] and most recently through a working group study on an EU-approved support mechanism for fossil-free flexibility.[12] Overall, a capacity market is a very challenging to legislate. It is noteworthy that in Ireland, where they have suffered from an electricity shortage, a capacity market is in use. Ireland's experience[13] has shown that it is possible to spend a lot of money on a capacity market without achieving the desired effects.

2.2.2 The amount of surplus electricity in the future

In addition to the fact that changes in the power balance in the Finnish electricity system pose challenges to power management, the changes have also increased price fluctuations under normal conditions and brought longer periods of very cheap electricity to Finland. Electricity consumption has always varied, but nowadays this variation is combined with variation in electricity production and increases the requirement for flexibility in the rest of the system.

In 2021, weekly variation in wind power (figure 8), i.e. the difference in electricity production between the least windy and the windiest hour of the week, was less than 3 000 MW. At the same time, weekly variation in consumption was at most 4 500 MW. These maxima do not usually occur at the same time, so the combined variation is smaller than the variations separately. The combined variation in 2021 was about 6 000 MW per week. In 2024, combined variation was at most as high as 9 000 MW per week. The need for flexibility in the rest of the electricity system has therefore grown by 3 000 MW in three years.

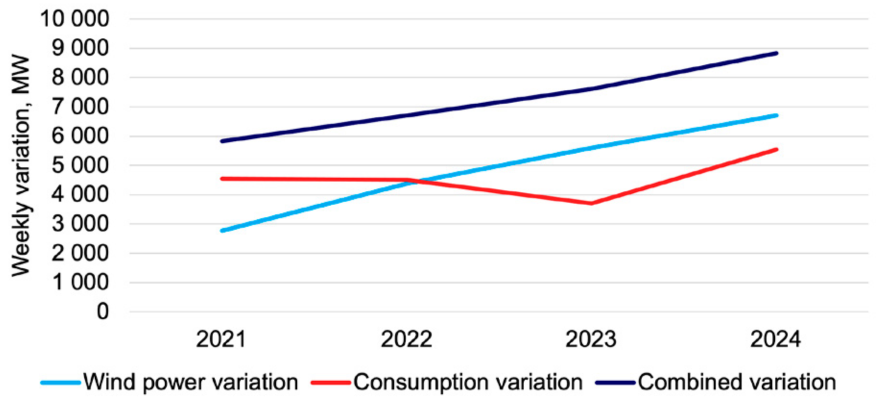


Figure 8. Annual development of wind power and consumption variability. The combined variability is smaller than the combined variability of consumption and wind power. However, it has also increased significantly.

[9] Price control in the Iberian Electricity Market (MIBEL)

[10] Temporary Emergency Generation

[11] Kapasiteettiratkaisuiden arviointi sähköriittävyyden varmistamiseksi Suomessa

[12] Fossiilittoman jouston työryhmän loppuraportti

[13] Kapasiteettimarkkinan haasteet – kokemuksia Irlannista

The need for flexibility in the electricity system has increased by 3 000 MW, but at the same time flexible production has decreased. As a result, electricity is cheap in Finland, but electricity price volatility is high. Figure 9 shows the placement of Finnish electricity prices on the volatility-average price axes.

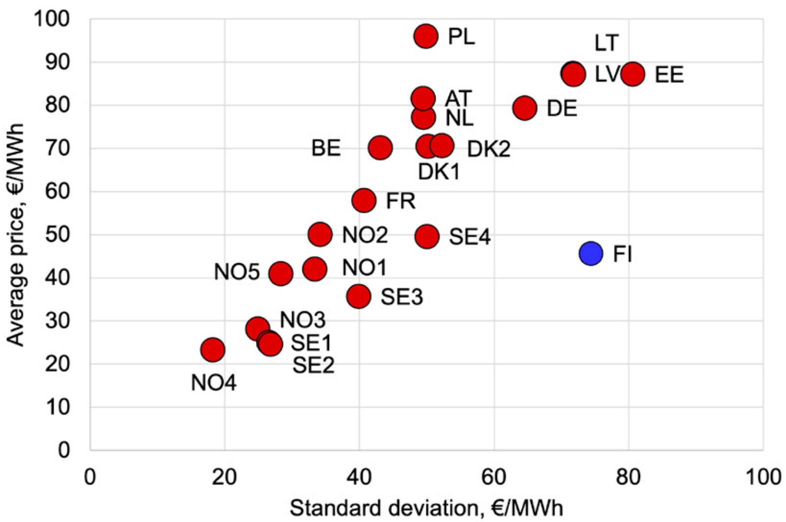


Figure 9. The standard deviation and average price of electricity prices in a few different bidding regions in 2024. The Finnish price area (FI) stands out clearly from the rest.

The low average price and high volatility mean that at the same time the threat of electricity shortages during cold, low-wind weeks is increasing and electricity is too cheap to make investments in electricity production worthwhile. Wind power producers are even reporting negative operating results.[14]

In 2040, surplus electricity could be utilised better than now. At the same time, however, renewable energy production capacity is expected to continue growing, although more moderately than before. Wind power is still the cheapest way to produce energy in Finland, and solar energy will also increase. We therefore anticipate that surplus electricity will be available during windy weather far into the future, and flexible electricity consumption will be profitable through centralised heating systems.

2.2.3 Non-combustion electricity system

In this chapter we examine the possibilities of a non-combustion electricity system. First, however, it is necessary to consider what types of proposals cannot be accepted. In scenarios for emission-free and non-combustion energy systems, it is possible to shift emissions and costs outside the system under examination. Here are some common hidden assumptions that are easy to make by mistake if they are not specifically avoided:

- **The need to balance the electricity system is shifted to neighbouring countries.** In modelling, imports and exports can be unlimited and at any time. In reality, variable production strongly correlates with neighbouring countries. If capacity is assumed always to be available, it is based on the assumption that neighbouring countries do not reduce their own non-variable production. If imports in the current electricity system were accepted as non-combustion during extreme frost, it would be based on the assumption that coal power from Germany via Sweden and oil shale burning in Estonia are counted as non-combustion.

- **The need for sufficient electrical power is not addressed.** This can happen if modelling is done at an annual or seasonal level, for example, as with the Guarantees of Origin system. In modelling, large amounts of wind and solar power are added so that over the year more electricity is produced than needed. In reality, calm periods and heating demand peaks must also be covered.

- **Unrealistically large amounts of demand-side flexibility are used without explaining where it comes from.** By analysing electricity exchange offer curves, it can be seen that demand-side flexibility available during extreme

[14] Ilmatar Energy Oy - Taloustiedot | Suomen Asiakastieto Oy

frost is at most about 2 500 MW. Part of this is short-term flexibility that cannot be continued for a whole week. In modelling, thousands of megawatts of demand-side flexibility are sometimes assumed following wind power production, i.e. demand flexes even for a week at a time. For scale, Tampere's current electricity consumption peak is about 400 MW. Proposing demand-side flexibility that includes several large cities is implausible, especially in a scenario where heating is fully electrified. A heating system that does not work during extreme frost is not acceptable.

Possibilities for non-combustion electricity imports

At present, in peak consumption situations part of Finland's electricity power need is covered by gas CHP and fossil condensing power imported from Estonia. The Aurora Line reduces this need but does not eliminate it during the coldest periods. If the electrical power requirement during severe frost grows from the current level, it will need to be covered by the most expensive fossil electricity available, i.e. imports from Estonia. To eliminate this dependence, electricity production in Finland would have to be increased or electricity production in Estonia would have to change.

Estonia plans to phase out oil shale use by 2035. Finland's power balance management will be complicated by the fact that Estonia plans to phase it out in the same way as Finland did, i.e. by increasing use of variable renewable energy and relying on imports from neighbouring countries in power shortage situations. The same approach is being repeated across the other Baltic countries. They plan to increase the use of wind power, and during calm periods they will rely on existing plants and imports.

It is therefore not sustainable to outsource the power problem to neighbouring countries and to describe an import-based electricity system as non-combustion.

Possibilities for non-combustion electricity production

If we want to produce electricity power ourselves, there are few non-combustion options. Because the need for peak production is rare, the solution would have to be inexpensive in terms of capital costs. Operating costs are less significant.

Non-combustion electricity production methods are variable production, i.e. wind, solar and hydropower. In addition, geothermal energy in volcanic areas and nuclear power are non-combustion. If unprofitable prototypes are excluded, there are no other non-combustion electricity production methods. All listed technologies are capital-intensive.

Non-combustion electricity production is not a cost-effective solution for covering rare consumption peaks.

Possibilities for non-combustion electricity storage

Energy storage does not produce non-combustion electricity, but it can shift non-combustion electricity from surplus periods to shortage periods. Electrical batteries and pumped-storage plants therefore make it possible to cover electricity consumption peaks partly using non-combustion electricity production.

In electricity storage, the difference between intraday and week-long power shortages must be recognized. Energy storage in electric batteries works on a daily basis and can reduce combustion in a short shortage situation, but covering a week-long period of low wind with electricity storage (chapter 3.2.1) or pumped storage (chapter 3.2.2) would be extremely expensive.

2.2.4 Adequacy of electrical power

There are no inexpensive non-combustion sources of peak electricity power, and it does not make sense to pay any price to avoid very rare electricity shortages. In VOLL reliability standard calculations, the cost of electricity shortages is set at €8 000/MWh. We should not pay more than this to prevent electricity shortages; rolling blackouts would be cheaper.

- **VOLL** – *Value of Lost Load* → an estimate of the economic harm caused to consumers by undelivered electricity (€/MWh).

Politically, it has been decided that we want reliable electricity, but not at any cost. The acceptable level of reliability is determined by the government. In Finland, the government-approved reliability standard is LOLE 2.1 hours/year with an EENS target 1 100 MWh/year.

- **LOLE** – *Loss of Load Expectation* → the expected number of hours per year when demand cannot be met.

- **EENS** – *Expected Energy Not Served* → estimate of how much energy is not delivered annually (MWh).

Electricity adequacy is monitored by ENTSO-E, the European Network of Transmission System Operators for Electricity. According to their calculations, electricity in Finland will still be sufficient in 2026, with a LOLE value of 0.3 hours/year. However, the situation is deteriorating rapidly. In 2028, LOLE will already be 4.0 hours/year, which is twice the accepted level in Finland. Without additional measures, the shortage will worsen further, and by 2035 the LOLE will already be 7.9 hours/year. In analysis by ENTSO-E, the growth of variable renewables and the resulting phase-out of fossil production mean that in disturbance situations we will run out of ways to manage shortages.[15]

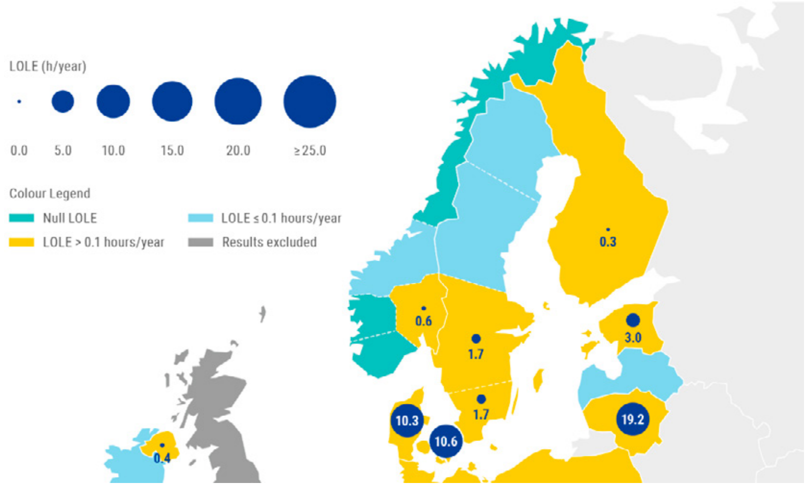


Figure 10. In 2026, electricity shortage hours will be at an acceptable level.

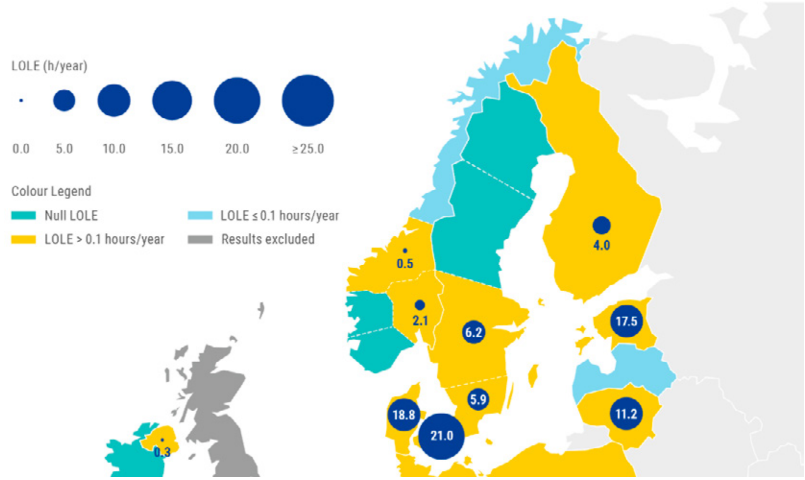


Figure 11. In 2028, electricity shortage hours will be above the approved level.

[15] ERAA 2024 Edition

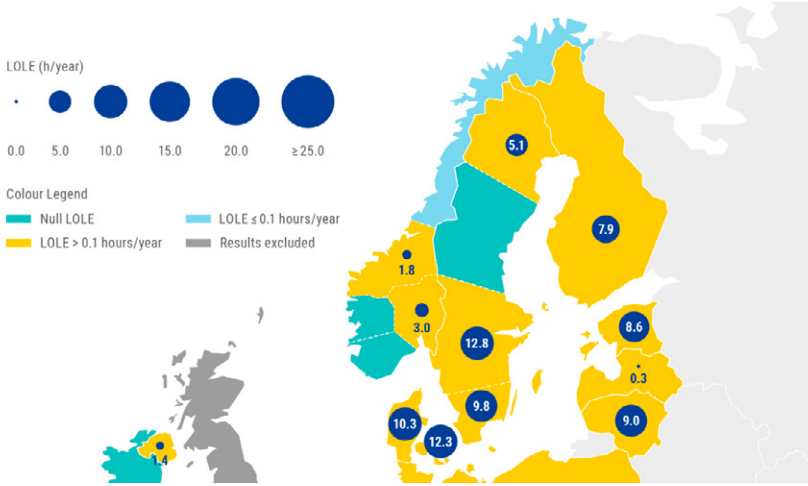


Figure 12. In 2035, electricity shortage hours will be almost four times higher than the approved level.

LOLE is a scenario-based expectation value, i.e. an average, which hides large variation between years. In 2035, LOLE will thus be 7.9 hours/year, but in median scenario years the LOLE value will be 0. This means that in more than half of the scenario years there will be no electricity shortage at all, while in the worst years the shortage will be significant. In 5% probability shortage years, LOLE rises to 51 hours/year and EENS to 23 GWh. Even this may seem reasonable: that about once every 20 years we may experience a two-day electricity shortage. In Finland, electricity shortages coincide with calm, cold weather lasting several days, possibly combined with failures in nuclear plants or transmission lines. Together, this would mean that during an extremely cold week there would be 51 hours when the electricity price is €4 000/MWh and, in addition, blackouts occur.

Demand-side flexibility is always activated in ENTSO-E models if the electricity price is too high. This is not harmless shifting of demand from one hour to another, but cutting demand, such as shutting down factories. If the electricity price is €2 000/MWh for a whole day but rolling blackouts are avoided thanks to voluntary demand cuts, technically we do not have a shortage. In common sense terms, however, such a week would mean a severe electricity shortage.

In summary, unfavourable weather, especially combined with nuclear plant failures, would temporarily cause very large disruptions to society. Figures 10–12 also show that the situation is the same across almost all of Europe, including our neighbouring countries. So far, adequacy of electrical power has relied on imports. The availability of imported electricity power is expected to weaken in the coming years.

ENTSO-E proposes demand-side flexibility and that 680 MW of new gas turbines are installed by 2030. In addition, 3 500 MW of gas turbines are proposed for southern Sweden in price areas SE3 and SE4. ENTSO-E warns that market signals may not be sufficient for capacity to emerge on a market basis, because shortage situations are rare.

A cross-border electricity shortage approved by the Finnish government is therefore just around the corner. The aim of this report is to identify obstacles to transition to a non-combustion energy system. The electricity system's power problem is developing so that the proposed solution at the European level is fossil gas turbines, which are inefficient. There are numerous obstacles to the transition in the electricity system.

3 Heating cities using the electricity system

In this chapter we examine the scenario where, in addition to ENTSO-E's forecast, district heating would be abandoned and Finnish cities would be heated using technologies that rely on the electricity system. In particular, we analyse which additional requirements this would bring for electricity system power management. We also examine how much power management would cost with non-combustion and combustion-based technologies. We find that by building gas turbines, the power shortage in the electricity system could be solved, but with non-combustion technologies the problem is too expensive to solve.

It is possible to design a completely non-combustion energy system. Finland's combined peak electricity and heating consumption is about 30 000 MW. If, for example, we converted all heating to direct electric heating and built 30 000 MW of nuclear power, most of which would stand unused for most of the year, the system would be non-combustion. Our argument is therefore not that transition to non-combustion in the electricity system is impossible, but that the solution may be cost-inefficient. Society has limited resources, so this matters. Whether the goal is to be combustion-free or to have a carbon-negative society, a more expensive transition is a slower transition.

In our scenario, a heating system based on electricity is implemented together with ground-source heat, which significantly improves the efficiency of electricity use in heating compared to direct electric heating. A Finland-wide scenario based entirely on ground-source heat is not realistic, but its simplicity brings clarity. The purpose of the scenario is to illustrate how the spread of electricity-based heating systems would affect the whole electricity system. These observations can also be applied to smaller transitions from district heating to ground-source heat, since the cost increase is roughly linear. Within the limits of calculation accuracy, the scenario can be used to estimate impacts for example in a 40% transition, as is discussed in chapter 6.3.

The additional electrical power need arising in the scenario must be added to ENTSO-E forecasts. According to those forecasts, electricity shortage is already coming, but a large transition to ground-source heat would worsen the situation. Naturally we do not model with ENTSO-E's precision, but we aim to use clear scenarios that are easy to adjust if the reader does not find them credible. Readers not interested in these details can skip to chapter 3.5 Summary of scenarios.

The modelled electricity-based heating system consists of two components: ground-source heat pumps and auxiliary electric heating. In this work, the COP (Coefficient of Performance) of the ground-source heat pump is assumed to be 3. The heating power requirement has been estimated based on district heating demand, and the ground source heat pump has been adapted to this using three different methods to obtain a range for the required electrical power.

Model 1, economic optimization

The first model is an economic optimization, where ground-source heat is dimensioned for a significant partial power. The electricity consumption of this system increases sharply in freezing weather, because the additional heat required is then taken from the auxiliary electric heating. The pump is sized so that the energy coverage of the ground-source heat pump in the heating season 2023–2024 would have been 96%. In this case, the power coverage would have been 57%. Power coverage means how much of the energy produced during the year is produced by the heat pump, i.e. in Figure 13 this is shown by the ratio of the blue area to the total area. Power coverage means how much of the power during peak consumption hours is produced by the heat pump. The rest of the energy and power are produced by the electric auxiliary electric heating.

It is noteworthy that in January 2024, the dimensioned temperature of Tampere was not quite reached. Extrapolating to the dimensioned temperature conditions, the power coverage would have been a few percentage points lower, approximately 54%. Although model 1 is close to the economic optimum in terms of history, the risks of heat sufficiency and electricity prices in extreme cold would be high. Understandably, this worries investors in ground-source energy. Projects designed for such a small power coverage have been built, but to our knowledge, only a few. Therefore, the model acts more as an upper limit for power demand, not as a forecast of likely development.

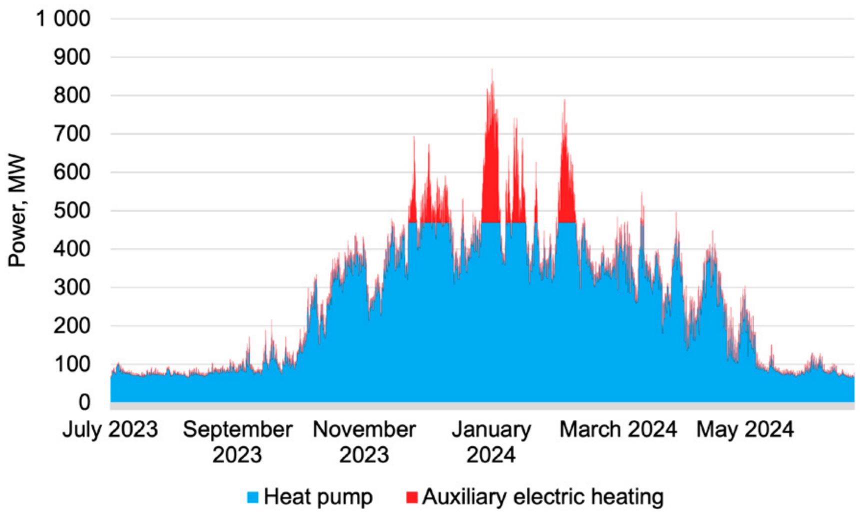


Figure 13. Distribution of annual heat production between heat pumps and electric boilers in model 1, on the Tampere scale.

The table below describes what a system according to model 1 would look like on both the Tampere and Finnish scales.

Table 1. Model 1 power requirements.

	Tampere	Finland
Heat production 2024	2.2 TWh	35,5 TWh
Transferred thermal power	900 MW	14 500 MW
Compressor electrical power	160 MW	2 600 MW
Auxiliary electric heating	410 MW	6 700 MW
Total electrical power	570 MW	9 300 MW

Model 2, based on observations

The second model is the method used in Mäki-Turja's master's thesis,[16] based on actual observations. In the work it was found that ground-source heat facilities can be divided into three categories.

1. Full-power dimensioned systems, where electricity consumption depends linearly on outdoor temperature.
2. Partial-power dimensioned heat pumps, whose increase in electricity consumption accelerates in severe frost, when auxiliary electric heating produces additional heat.
3. Under-dimensioned heat pumps/hybrids, whose increase in electricity consumption stops at about -15°C, when the maximum output of the heat pump is reached.

[16] Siiri Mäki-Turja, Maalämpökerrostalojen vaikutukset sähkönjakeluverkkoon, diplomityö, Tampereen yliopisto, Automaatiotekniikan DI-ohjelma, 2025.

When these three observed archetypes are combined, weighted with the realised numbers, the result is that as a group heat pumps behave like full-power dimensioned ground-source heat, albeit perhaps with a slightly lower COP value than if they were truly full-power dimensioned. Model 2 therefore gives the lower bound of our range for required additional electricity power.

Facilities whose electricity consumption do not increase below -15 °C were surprisingly common. This means that they have some other heat source in use or they are severely under-dimensioned. Since the scenario under examination is a 100% transition to ground-source heat, district heating hybrids would be impossible in this scenario. Our report deals with non-combustion heating, and wood heating or old oil boilers are of course not non-combustion. Systematically under-dimensioned heating systems, which in severe frost would allow buildings to cool by more than 10 degrees, are also not acceptable. Therefore category 3 hybrid sites should be excluded from the observations. In this case, electrical power requirements would grow by about 7%. However, in this report we do not make such a correction, and the estimate based on Mäki-Turja's calculations serves as the lower bound of the range.

In the thesis, the electrical power requirement was estimated for a 50% transition of apartment buildings from district heating to ground-source heating, and the result was 87 MW. About 50% of Tampere's heating volume comes from apartment buildings. Thus a 100% transition in the whole building stock would result in an electric power increase of 87 MW x 2 (not only apartment buildings) x 2 (100% transition instead of 50%) = 348 MW in Tampere. This includes both compressors and auxiliary electric heating, so they are not separated in the table. This is a rough estimate. Although Mäki-Turja's estimate is based on careful analysis, scaling to other building types, in particular, is very imprecise

Table 2. Model 2 power requirements.

	Tampere	Finland
Heat production 2024	2,2 TWh	35,5 TWh
Transferred thermal power	900 MW	14 500 MW
Compressor electrical power		
Auxiliary electric heating		
Total electrical power	350 MW	5 600 MW

Model 3: based on realised plans

The third model is based on the plans of sites that have switched away from district heating or have considered doing so. This represents, to the best of our knowledge, typical dimensioning. Typically, energy coverage has been 98–99%, and power coverage about 60–70%. We model the system so that we take the 2023–2024 realised data and fit to it a 70% power coverage. Relative to the dimensioning conditions, the power coverage is then 66% (with maximum power in 2024 at 870 MW, design power about 900 MW). Over the review period, energy coverage is 98.6%.

Table 3. Model 3 power requirements (calculated from dimensioning conditions)

	Tampere	Finland
Transferred thermal power	900 MW	14 500 MW
Compressor electrical power	210 MW	3 400 MW
Auxiliary electric heating	270 MW	4 400 MW
Total electrical power	480 MW	7 800 MW

Table 4. Model 3 power requirements (calculated by actual use, **this model is used in subsequent calculations)**

	Tampere	Finland
Heat production 2024	2.2 TWh	35,5 TWh
Transferred thermal power	870 MW	14 000 MW
Compressor electrical power	203 MW	3 300 MW
Auxiliary electric heating	261 MW	4 200 MW
Total electrical power	464 MW	7 500 MW

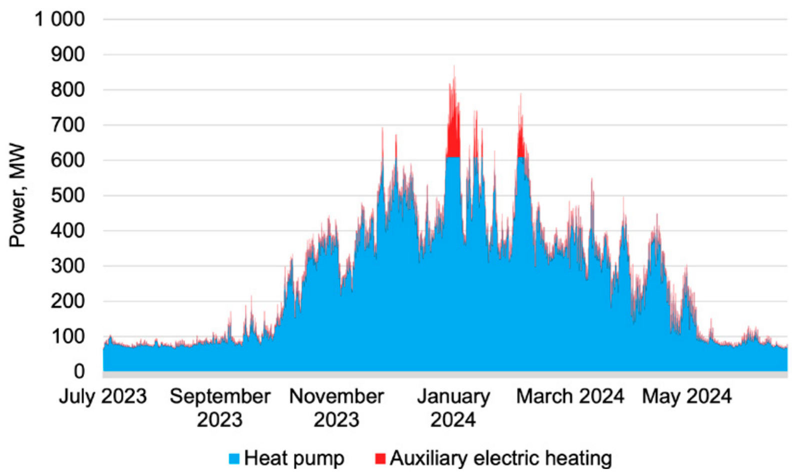


Figure 14. The distribution of annual heat production between heat pumps and electric boilers in model 3, on the Tampere scale.

The amount of heating energy produced by electric boilers is very low in the big picture (Figure 14). If we look at the consumption during the dimensioned week and instead of heat production, we look at electricity consumption (Figure 15), the electric boiler stands out in a completely different way. Although 99% of the heating energy came from heat pumps, more than 50% of the electricity demand came from electric boilers. This 1% is a fairly minor detail in the design of a building-specific heating system, but at the system level this is the factor that could bring down the entire electrical system.

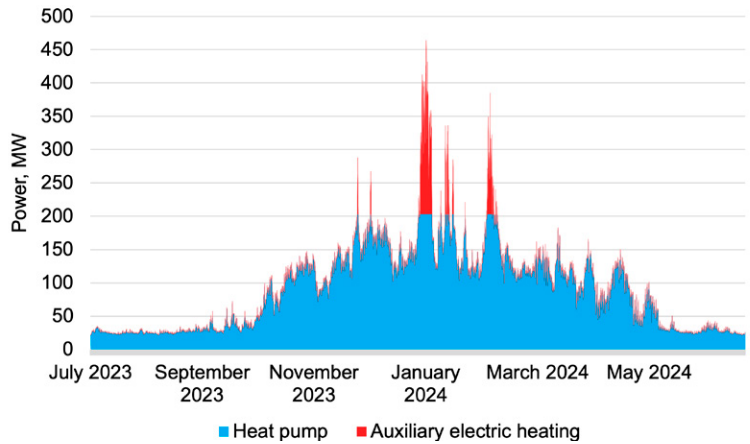


Figure 15. Distribution of annual **electricity consumption** *between heat pumps and electric boilers in model 3, on the Tampere scale.*

What makes this feature particularly unfortunate is that in mild winters the system appears to be putting very little strain on the electrical system. Only in the most severe frosts does the site's electricity consumption double. Table 4 estimates that the consumption of auxiliary electric heating in a 100% transition would be 4,200 MW. Even a smaller transition can be serious for the electrical system if it is rapid and occurs latently during mild winters. While the transition is underway, measurement data on the electrical output of heat pumps is available even in mild years, and this does not come as a surprise. However, the power of auxiliary electric heating can come as a surprise, because they are not used in mild years. In this case, at the Finnish level, with a 10% transition, electricity consumption in the most severe frost is suddenly 420 MW higher than expected.

There is also evidence for unexpected growth in electricity demand. In September 2023, Fingrid estimated that on an extremely cold and calm winter day peak consumption would be about 14 300 MW. The realised peak in January 2024 was 14 993 MW, i.e. about 700 MW higher than expected. Fortunately, wind power production was better than the dimensioned conditions and electricity shortage was avoided.

For winter 2024–2025, peak consumption was forecast at 15 000 MW. Fingrid did not forecast that electricity consumption would grow from the previous winter, even though about 100 000 heat pumps were sold.[17] Most of these were small pumps and replacements for old ones, but from other sources we know that the transition from district heating to ground-source heat continued, for example in Helsinki. The winter was mild, so peak consumption remained at 13 300 MW. It seems inevitable that the next time weather is at January 2024 levels, peak consumption will have risen. Safety margins are very low, especially if the weather is calmer than last time. (Figure 16).

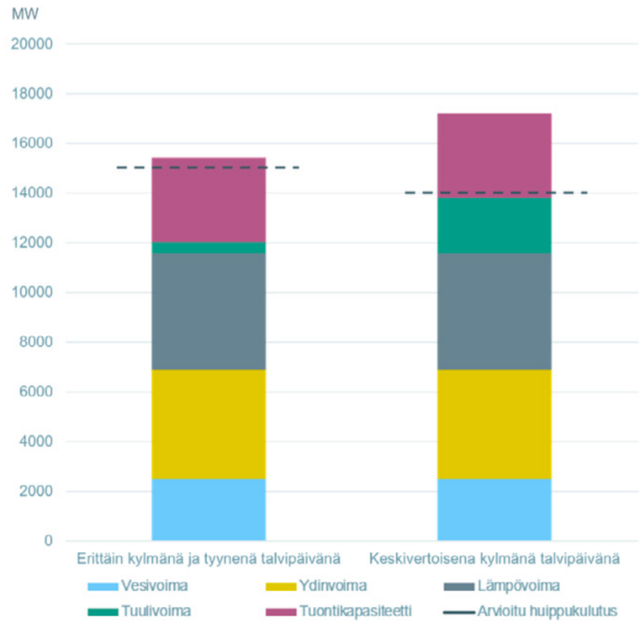


Figure 16. Electrical adequacy during the Finnish winter season 2024–2025.[18] From bottom up: Hydroelectric power, Nuclear power, Co-generation and Condensing power, Wind power, Import capacity. The dashed line is estimated peak demand.

The cost of heating when it relies on the electricity system

Based on the three methods described earlier, we estimate that electricity power demand would increase in Tampere by 350–570 MW and in Finland by 5 600–9 300 MW. In subsequent analyses we use Model 3 to describe changes in the electricity system. We use the realised data from winter 2023–2024, which comes close to but does not quite reach the dimensioned conditions. Calculated based on the dimensioning conditions, Tampere's heat power would be 900 MW and electrical power with the ground-source heat system would be 480 MW. Based on realised data, the maximum heat power would be 870 MW and electricity power 464 MW. Scaled to the whole of Finland, this equates to 7 500 MW of electricity power demand.

[17] Lämpöpumppujen myynnissä pudotusta 14 %. Kasvu-uralle palaamisen merkit jo nähtävissä.

[18] Sähkön riittävyys tulevana talvena edellyttää luotettavaa kotimaista tuotantoa ja tuontia

Investments would be required in electricity production (chapter 3.2), electricity transmission (chapter 3.3), electricity distribution (chapter 3.4) and of course in ground-source heat systems themselves.

In Tampere, we estimate that investment in ground-source heat systems for all district heating sites would total about €1.4 billion. Scaled to Finland, the investment would be about €22.6 billion. Chapter 3.5 provides a summary of all these costs.

3.1 Investments in electricity production

Below is a ground-source heating system according to model 3 described in the previous chapter, scaled to the whole of Finland for the heating season 2023–2024. The model assumes that wind power will be built into the electricity system with an equal annual energy to cover the growth in electricity consumption in order to support the transition. This is not a forecast, but rather the purpose is to illustrate the scale of the power management challenge. The base load could also be covered with, for example, nuclear power, but dimensioning this would have its own challenges, because the need for electric power increases 20-fold between summer and periods with the harshest frost. In Finland, it is windier in winter than in summer, so at a seasonal level, wind power follows the heating need better and is likely to be a more cost-effective solution. The model does not take into account the additional CHP power that would be required as a result of phasing out district heating.

Figure 17 shows how wind power could cover the electricity needs of the heat pump system. According to the model, there was relatively good availability of wind power during the coldest week, approximately 25% of peak power. Nonetheless, the need for additional power caused by the cold week is considerable. By increasing the amount of wind power, the need for other power could be reduced. However, since the availability of wind power during the dimensioned week was quite low, building additional wind power would not be a cost-effective solution to meet the need for peak power.

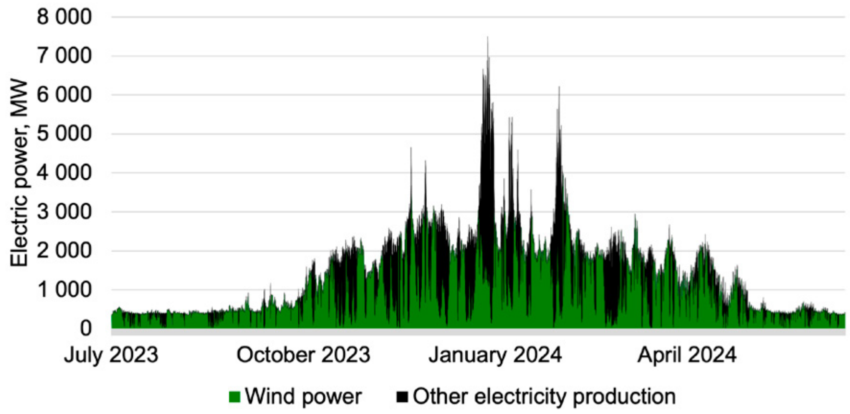


Figure 17. Modelled electricity consumption in winter 2023–2024. Electricity marked in green is obtained from wind power, electricity marked in black is needed from another source. Wind power production is at times greater than consumption, which is not shown in the figure.

The investment cost of wind power is approximately EUR 1.4 million/MW.[19] [20], With the assumptions made, slightly more than 0.65 MW of wind power is needed per MW of electricity consumption. On the Tampere scale, the amount of wind power needed would be 320 MW and on the Finnish scale 5 100 MW. The investment would be EUR 0.45 billion on the Tampere scale and EUR 7.1 billion on the Finnish scale.

In our empirical model, 5 100 MW of wind power produces 13.1 TWh of electricity, i.e. peak usage time is 29%. This is lower than is typically predicted in wind turbine plans. Most likely, this is partly due to the wind conditions during the 2023–2024 heating season, but is also partly due to the fact that, currently, the price of electricity turns negative during periods with strong wind. In this case, wind power producers do not benefit from producing free electricity. Fortunately, the low peak usage time does not interfere with our analysis, as we are mainly interested in one cold week, not energy use throughout the year.

[19] Swedish firm OX2 to spend €700m on two wind farms in Finland (luvuista johdettu 1,48 €/MW)

[20] Investoinnit - Suomen uusiutuvat ry

Of the modelled 13.1 TWh of wind power production, only some of it can be utilized in the ground-source heating system. The amount of wind power that can be utilized is 8.4 TWh (Figure 17, in green). The remaining 4.7 TWh is surplus electricity, which is generated when the heating demand is low and there is a lot of wind in Finland. In fact, there is no single hour when the country's entire wind power production can be utilized. The maximum power that can be utilized from wind power is about 4 000 MW. Without district heating networks, it is unclear for what purpose this surplus electricity could be utilized, especially when considering that this over-production would come in addition to the over-production that is already occurring.

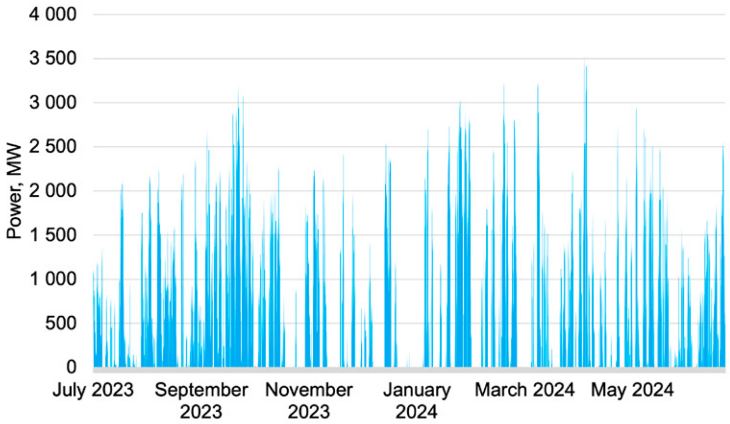


Figure 18. Wind power production not utilised in the model, also known as wasted electricity.

The maximum instantaneous need for other electricity production would be 6 300 MW. In our model, wind power therefore cuts the peak power requirement by 1 200 MW, or 16%. It can be assumed that the short-term need for electricity would be covered by hydropower balancing, electricity storage and demand-side flexibility. In other words, we would not need 6 300 MW of balancing power. We could certainly cope with short peaks. However, a cold week with little wind, such as the first week of January in the model, would still remain a problem. The maximum seven-day energy requirement is 680 GWh. As stated in section 2.2.3, the non-combustion alternatives available in the electricity system are very expensive and energy storage is the most cost-effective non-combustion alternative. With energy storage, capacity is more expensive than power, so the weekly energy requirement will be the basis for our cost calculation.

Our model is greatly simplified. The model does not include demand-side flexibility, regulation of existing hydropower or other components that vary according to demand. Nonetheless, it is still a reasonable illustration. As we state in Section 2.2.4, the electricity system is already moving towards a power shortage, even if there is no widespread transition to electricity-based heating. The ENTSO-E models have thousands of megawatts of demand-side flexibility and still the system is approaching a power shortage. In this scenario, we increase the need for electrical power by using electric heating. The sharp peak in power this demands comes precisely when the electricity system is otherwise short of capacity. Therefore, there would be no significant unmodeled free flexibility available in the system here. Our intention is not to find an optimal path to combustion-free heating, but to increase understanding of its requirements. The following simplified calculations serve this purpose.

It is reasonable to assume that "other electricity production" during a cold, low-wind week must be new production, especially if we want it to be combustion-free. However, it is assumed that the flexibility of the heating systems would itself alleviate the need for additional production. To take this into account, instead of seven-day dimensioning, a five-day dimensioning period is chosen. The maximum five-day energy demand, i.e. the energy demand during the cold, low-wind week being dimensioned, would then be 550 GWh. When power is required in the dimensioning, we use an average power of approximately 4 600 MW. Scaled to Tampere, this corresponds to 35 GWh of energy storage and 280 MW of average power.

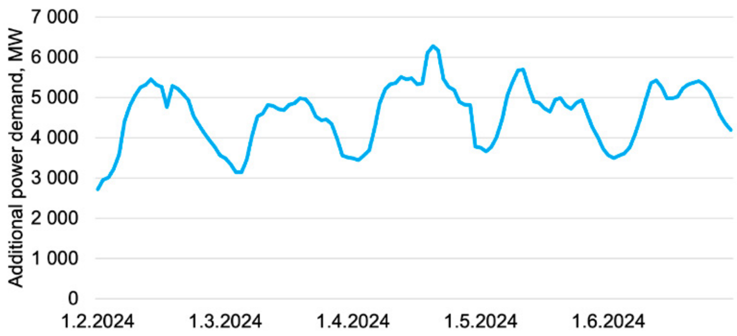


Figure 19. In addition to wind power, the energy demand in Finland during the five-day period to be measured, a total of approximately 550 GWh.

Such cold weeks do not occur every year. The beginning of 2024 was the coldest week in 20 years in Tampere. However, weeks that are nearly as cold occur about every five years. We assume in our calculations that cold, windless weeks occur once every five years. In the next chapter, we will examine how this additional power could be produced.

3.2 Fossil-free flexibility

The non-fossil flexibility support mechanism is a support system currently under consideration in Finland. Its aim would be to aim to strengthen the security of electricity supply by supporting flexible, capacity for fossil-free electricity production. According to the final report by the Ministry of Economic Affairs and Employment's non-fossil flexibility working group, the support mechanism would be in the form of investment aid based on a competitive tendering, and would support electricity storage, demand-side flexibility or forms of flexible production capacity that are not based on fossil fuels. Support could be provided for both new investments and to extend the service life of existing capacities. The mechanism is based on the EU Electricity Market Regulation (Articles 19e–19g), which requires Member States to define a fossil-free flexibility target and to establish a support system if market-based solutions are not sufficient to achieve their security of supply targets (Chapter 2.2.4).

The working groups preparing the mechanism have had different views on which challenge the new capacity would primarily address. Do we want the capacity to handle a cold, windless week or price peaks around the year? Do we want to prevent power outages or try to reduce electricity price fluctuations?

The problem we should focus on is how to handle a cold, windless week.

Electricity price variation is not a fault in Finland's electricity system; they are a feature. Wind power is the cheapest form of electricity production in Finland, and its output varies. On average, electricity is cheap, so occasional high prices are not a problem. In the electricity market, supply for intraday regulation grows on a market basis. There is already a functioning market model for Day-Ahead and Intraday flexibility, and it does not require public support. Market-based development will, in part, smooth out price variations. In addition, consumers can protect themselves against price fluctuations with electricity contracts if they wish. **If non-fossil flexibility support is directed at these market-driven emerging markets, it will distort competition and taxpayers' money will be wasted.**

By contrast, if a situation occurs where there is the risk of an electricity power shortage for several consecutive days due to cold and calm weather, it cannot be solved under the current rules on a market basis, as noted in chapter 2.2.1. If a support mechanism procures reserve power only for the worst cold, windless week, its value would be zero in normal circumstances, possibly for years. In a crisis situation, when it inevitably arrives, its value would be very high. The state already has such holdings, for example F-35 fighter jets or the National Emergency Supply Agency's fuel reserves. Providing such a public good fits the state's core tasks.

When electrical power runs out, we have an unpleasant but necessary management tool: rolling blackouts. There has to be a limit to what we pay to prevent electricity shortages. In reliability standard calculations, the cost of an electricity shortage is set at EUR 8 000/MWh.[21] If the cost of avoiding a shortage is more than this, it is in society's overall interest to accept occasional shortages. In a well-designed electricity system, shortage situations are very rare.

The problem with supporting non-fossil flexibility – by whichever mechanism – is the inevitable market distortion and the significant costs this brings to the national economy. Partly for this reason, the EU sets strict limits on support arrangements for electricity systems.

In practice, large-scale non-fossil flexibility can be implemented in the electricity system with renewable fuels, energy storage or demand reduction. In district heating systems, producing peak power is significantly cheaper than in the electricity system. In a non-combustion system it is handled with district heating storage. If combustion is accepted as a solution, it would also be much more energy- and cost-efficient to use it in the district heating system than in the electricity system. These alternatives are examined in the following chapters.

The real solution will be a combination of market-based partial solutions and reserve power, supported by society or created by a new market mechanism. The following example calculations compare technologies in a situation where the aim of the investment is only to solve the cold-week problem. Batteries, demand-side flexibility solutions and pumped-storage hydroelectric plants that freely participate in the market will in part help solve the power shortage, which is excellent. The more market-based flexibility solutions emerge, the less public support is needed. However, this is not a reason to subsidise electric batteries when the purpose is to resolve the remaining power shortage. If subsidised batteries are allowed to participate freely in the electricity market, the market would be heavily distorted, market-based batteries would be displaced, and taxpayers' money would be wasted. If, on the other hand, batteries are not allowed to participate freely in the market, we would arrive at the situation examined in the following chapters, where any benefit will only be gained during the rare shortage situations.

3.2.1 Solving a week-long power shortage with electric batteries

Electric battery storage is very well suited to intraday balancing, but when applied to a week-long power shortage, they become extremely expensive. The purpose of the following example is to show that batteries do not work as a cost-effective solution to a power shortage. By subsidising batteries, short-term markets end up being distorted without actually solving the shortage.

For a 100% storage-based solution to a power shortage to work, the store must of course contain energy. Electricity storage systems typically have a very high discharge power relative to the size of the energy store. It would be in the interest of the system's owner to discharge the store into the market immediately during the price spike on the first day. Clearly, during a power shortage, electricity prices would fluctuate strongly, so it would be worth charging and discharging the store frequently. However, it might then occur that towards the end of the week the storage systems would be depleted and there would no good opportunity to recharge them. In the following scenario, it is assumed that the batteries are saved only for reserve power, so the batteries are dimensioned according to the energy needs of a low-wind week.

Example: Solving the power problem with a battery

In chapter 2.3.1 it was calculated that the need for storage capacity in Finland is 550 GWh. Based on a recent investment decision, the unit price of a battery for Oulun Energia turned out to be EUR 0.28 million/MWh.[22] At this price, the investment cost of solving the power problem would be about EUR 154 billion.

The price of battery technology has fallen rapidly, but batteries contain many components whose costs do not decrease. These include, for example, the design, electrical connections, fire safety systems and installation. Let us assume, very optimistically, that the price level of batteries could fall to one third of the current level, i.e. to EUR 0.1 million/MWh. In this case, the price of the required storage would be about EUR 55 billion.

[21] Energiaviraston päivitetty ehdotus valtioneuvostolle luotettavuusstandardista

[22] Oulun Energia panostaa sähköjärjestelmän joustokykyyn ja rakentaa Toppilaan suuren sähkön akkuvaraston

In addition, let's assume that the batteries could be fully charged with free electricity.

According to figures used by ENTSO-E, the economic lifetime of batteries is 8 years. Since batteries are used only rarely, it is assumed that they would in fact last 16 years. According to our assumption, the frost situation we are dimensioning for would occur once every five years, so the batteries would prevent 3.2 electricity shortages during their lifetime, i.e. a total of 550 GWh × 3.2 = 1 760 GWh. The fixed cost of the batteries would therefore be EUR 31 000–88 000 per prevented electricity shortage MWh.

In chapter 3.2 the value of a prevented electricity shortage was stated to be at most EUR 8 000/MWh. From the point of view of society's overall interest, it would therefore be cheaper to choose rolling blackouts than to solve the power shortage with subsidised batteries, even if the electricity were charged for free. There are alternatives to solving electricity shortages that are more than ten times cheaper. Costs are falling, but a slowdown is already observable. SolarPower Europe forecasts that the procurement cost of battery cells will fall by about 10% by 2030.[23] The cells themselves are only part of the total project cost, and it is difficult to see that design, electrical connections or other project costs would decrease significantly overall.

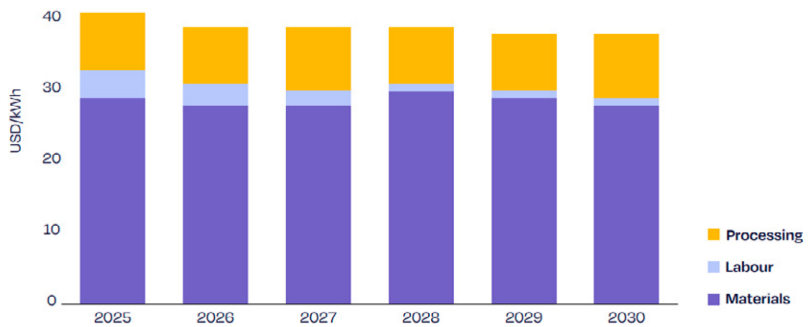


Figure 20. SolarPower Europe predicts that battery cell prices will continue to fall, but slowly. The average real price for LFP battery cells is shown in the figure.

Our example therefore shows that if (and in our opinion when) the only problem to be solved in the electricity system is securing sufficient electricity output during a cold week with little wind, batteries should not be subsidized by society. On market terms, batteries will certainly become more common, and they will play an important role in the electricity system of the future. However, they are not a silver bullet for power shortages.

3.2.2 Solving a week-long power shortage with pumped-storage

Of the projects that have been publicly announced, the most affordable pumped-storage plant is the Ailangantunturi project on the Kemijoki River. The project's environmental impact assessment states that the maximum volume of the upper reservoir is 13 million m^3 and the fall height is about 200 m. The potential energy $E \approx \rho \cdot g \cdot h \cdot V \cdot \eta$ gives roughly 5.7 GWh, assuming an efficiency of η=80%. The calculated value is an order-of-magnitude estimate; the final figure depends, among other things, on operating limits and efficiency. Kemijoki has announced an investment cost range of EUR 600–800 million.[24] This would give an energy storage cost at best of about EUR 0.1 million/MWh. The service life of a pumped-storage plant is, however, considerably longer than that of batteries; we assume a lifetime of 40 years. If we assume that this project – the most affordable in Finland – could be scaled up one hundredfold without costs rising, the price would be €12 400 per prevented electricity shortage MWh. A pumped-storage plant is therefore a better solution than a battery, but not sufficiently cost-effective to solve the problem on its own.

3.2.3 Solving a week-long power shortage with thermal storage

In our scenario, the district heating networks have been shut down. However, to improve understanding, we also include comparisons of some power-management methods that can be used within a district heating network. Storing energy in a heat reservoir is very cheap compared with storing it in electric batteries. This is why such they typically have a large storage capacity relative

[23] European Market Outlook for Battery Storage 2025-2029

[24] Jokiyhtiö kaavailee pumppuvoimalaa tunturin sisään – hallitus näyttää vihreää valoa

to their discharge power. For example, in Oulu's electric battery system the discharge power is 20 MW and the storage capacity 40 MWh. By contrast, Vantaa's Varanto thermal energy storage facility has a discharge power of 200 MW and a storage capacity of 90 000 MWh. If the discharge power of the heat storage was in the same proportion to capacity as in a battery, the discharge power would be 45 000 MW — three times more than the peak district heating demand of the whole of Finland. Increasing discharge power relative to capacity would not be expensive, so the limitation is more a matter of need than of cost.

Despite rising costs during the project, Vantaa's Varanto is still quite cost-effective. For about EUR 220 million, it provides a 90 GWh energy store. The cost also includes electric boilers, so it is comparable with an electricity storage system. In a district heating network, energy is stored using electricity and discharged as heat. In the case of Varanto, the price of the store is about EUR 2.4 million per GWh. However, not all district heating networks are suited to massive storage like Vantaa's Varanto. For another comparison, we use Tampere's district heating reservoir and electric boiler project. In this project, 100 MW of electric boilers and two reservoirs with a combined storage capacity of 800 MWh are being built. The project cost is about EUR 20 million. This gives a specific storage cost of EUR 20 million/0.8 GWh = EUR 25 million/GWh, and the charging and discharging powers are fully sufficient for the needs of our example. The five largest district heating networks cover about 40% of district heating consumption. For these networks we can assume that a seasonal reservoir excavated into bedrock would be feasible on a practical scale. For other networks, smaller district heating reservoirs could be built.

Example: Solving the power problem with thermal storage
The storage need in Finland is 550 GWh. About five storage facilities similar to Varanto would be required. Calculated at its specific cost, the total expense would be EUR 1.3 billion. Using Tampere's district heating thermal stores as a reference, a total of 1 375 units would be needed, together with electric boilers amounting to 69 000 MW — far more than actually required. The cost, about EUR 13.8 billion, therefore represents the upper bound of uncertainty, because with heat reservoirs the savings from scale are considerable, as can be seen from the comparison between Varanto and Tampere's Lielahti project.

As with electric batteries, district heating thermal storage can be used for other purposes, and not just to prevent electricity shortages. However, we will calculate in the same way as in the electric battery example, with the assumption that they have been built solely to prevent electricity shortages. As in the example with electric batteries, it is assumed that the thermal storage can be replenished using free electricity. A district heating reservoir technically has a much longer life than an electric battery, and we use a depreciation period of 40 years.

The cost would be EUR 300–3 100 per avoided electricity shortage MWh.

3.2.4 Solving a week-long power shortage using combustion in the electricity system

Burning natural gas is neither combustion-free nor fossil-free energy production. Biogas and hydrogen produced from renewables are renewable, but they are not combustion-free. We nevertheless consider these as alternatives so that the study's objective of "increasing understanding of the challenges of the transition" is fulfilled. In the case of combustion-based solutions, the deciding factor is not energy demand but the required power. Unlike energy storage, once sufficient power capacity has been built, it can be used as long as is needed.

Appendix 9.1 discusses Ireland's experiences in resolving electricity shortages with engine power plants. A 650 MW procurement for five years cost an estimated EUR 337 million per year. Ireland's costs included not only the investment but also all operating and maintenance expenses. The sum is still extremely high. A significant factor here is EU legislation, which requires the procurement to be temporary and prevents reserve capacity from participating in the electricity market. Ireland's experience therefore provides an upper limit for the cost. In Ireland, the fuels for backup power are natural gas and diesel.

Example: Solving the power problem using the Irish model

The power demand during the dimensioned week in Finland would average 4 600 MW, with an energy demand of 550 GWh for the week, and shortage weeks occurring once every five years. We assume that battery and other flexibility solutions would smooth the power demand to this average level. If we apply Ireland's cost level of EUR 337 million per year to 650 MW, i.e. EUR 0.52 million per MW per year, then in Finland our scenario would cost EUR 2.4 billion per year.

At this price, preventing an electricity shortage would amount to €22 000 per MWh. This is therefore not a wise solution.

If longer discharge times are not permitted, it is not worth resolving the electricity power shortage, as rolling blackouts would be cheaper. However, if we take the view that the shortage of electricity capacity would be permanent and plants would be needed for 30 years, and no revolutionary cheap technology is invented to solve the rare power shortage, then the shortage could be resolved as follows:

Example: solving the power problem by investing in backup power plants

We assume that half of the power is provided by gas turbines with a specific cost of EUR 800/kW and half is provided by engine power plants with a specific cost of EUR 1 800/kW. According to the figures used by ENTSO-E, the economic life of a gas turbine is 30 years. In this case, the investment in Finland would be EUR 6.0 billion, meaning an investment of EUR 1 800 per avoided electricity shortage MWh.

If calculated with an efficiency of 40% and a fuel cost of EUR 200/MWh (half gas, half oil), the share of variable costs would be EUR 500/MWh.

Other operating and maintenance costs should be added to this in order to make the figures comparable with the Irish model. Let's assume the cost is 3% of the investment costs annually. In this case, the annual cost would be EUR 180 million. This would amount to EUR 1 600 per avoided electricity shortage MWh. We do not know the maintenance costs of emergency power plants well, but the cost has been conservatively estimated from several sources.

With current technology, gas combustion would generate emissions. A 550 GWh electricity shortage every five years would mean an efficiency factor of 275 GWh of natural gas consumption and 55 000 tonnes of annual emissions. Emissions can be reduced by using renewable or synthetic gases and oils. The cost of the emission allowance has already been taken into account in the variable costs.

Calculated using these figures, the price of an avoided electricity shortage would be EUR 3 900/MWh.

At this point, we need to consider how the presence of such peak electricity power would change the electricity market. If peak generation were allowed to participate freely in the electricity market, it would, based on the assumptions made in practice, set a price cap of EUR 500/MWh on the price of electricity, in line with variable costs. This would eliminate a lot of demand response from the electricity market, approximately 1 000 MW in the situation in Appendix 9.1. In other words, if peak generation is built with public money in a competitive market, we will never see how much investment we could have avoided by utilizing demand response. In the ENTSO-E calculations, demand-side flexibility for Finland was assumed to be at least 2 000 MW. If some of the demand-side flexibility was eliminated, more electricity production would be needed accordingly. The EU has good reason to be careful about how electricity production investments are supported. Therefore, the limit for market participation should be at least the price cap of the Day-Ahead market, currently EUR 4 000/MWh.

If the power shortage is to be solved by building new gas-based production capacity with state funding, it is important to start small enough. Even a small reserve gives time to act thoughtfully in a crisis situation. The Irish case is a cautionary example of how expensive it is to act in a hurry. Every extra megawatt of reserve power is a hugely expensive wasted investment.

Reserve power generators are often built into large data centres. If these could be harnessed as reserve power for the electricity system, the cost to society could be significantly reduced. In event of an electricity shortage, the price of electricity would be EUR 4 000/MWh or more on the intraday market, so incentives for utilizing capacity in a shortage situation would indeed exist. If operators are able to offer their flexibility to the market in advance, they will also have the actual ability to use reserve power generators in a shortage situation. The use of reserve power generators is limited, for example, by environmental permits. The continuous use of reserve power generators in a severe power shortage should be permitted in regulations. Their use would be minimal, but utilizing these production solutions, which are already installed, would save society significant costs.

3.2.5 Solving a week long power shortage using combustion in the district heating system

Burning gas in a district heating system is not any more combustion-free than in an electricity system, but at least it is more efficient. If the efficiency in electricity production is 30–50%, the efficiency in heat production is 90%, even in an old plant.

Example: Solving the power problem with gas

The power requirement in the dimensioned week in Finland would be an average of 4 600 MW. Pessimistically estimated, the specific investment in a heating boiler would be EUR 300 /kW and the total investment would be EUR 1.4 billion. The capital requirement would be significantly reduced by the existing old capacity. We use a depreciation period of 30 years for the investment, which gives a fixed cost of EUR 590 /MWh.

If we assume a fuel price of EUR 150/MWh, including taxes and emission allowances, and an efficiency of 90%, then the resulting variable cost would be EUR 167/MWh.

The operation and maintenance of remote heat-only heating plants is significantly cheaper than with more complex electrical power plants. Using the same 3% investment cost estimate, the annual cost would be EUR 41 million. This would amount to EUR 380 per avoided electricity shortage MWh.

The combustion of gas would generate emissions. A 550 GWh electricity shortage every five years would mean an efficiency factor of 122 GWh of natural gas consumption and 24 000 tonnes of annual emissions. The cost of the emission allowance has already been factored into the variable costs.

Using these figures, the price preventing an electricity shortage would be around EUR 1 100/MWh.

The use of a gas boiler would generate emissions. However, since the peak load plant would only operate during calm, extremely cold weather, the annual operating hours and emissions would be small. The emissions could be reduced by using renewable gases or oils.

3.2.6 The importance of supporting fossil-free flexibility in district heating

For district heating, the power problem that is emerging in the electricity system is both a threat and an opportunity. Our examples show that whether the solution is combustion-free or combustion-based, using district heating systems to solve the heating power problem is significantly cheaper. District heating systems support wind-based electricity systems exceptionally well.

Electric boilers can utilize surplus electricity that is unsuitable for other purposes, and CHP plants can produce electricity close to consumption, just when the shortage of electricity production and transmission is at its worst.

However, finding a solution to the power problem using public support would mean unpredictability in the operating environment and the conditions for fair competition. If the problems of electricity power management are solved, for example, by purchasing gas turbines with tax funds, it is a revenue transfer to alternative heating systems that compete with district heating, which rely on the electricity system to obtain peak power during times of shortage. The cost sharing of support mechanisms for power management in the electricity system must be based on the polluter pays principle, so that the support does not distort the electricity market, as well as also the heating market.

The price of electricity has fallen so low that the market situation is driving CHP plants that produce flexible power out of operation. The market signal is therefore that there is too much production and it should be reduced. The purpose of the non-fossil flexibility support mechanism is to create new production. When new supported capacity enters the market, it would drive old plants out of operation at an accelerating pace. In the worst case, this could lead to a spiral in which some kind of support is paid for all production. The risk of this is particularly high if the aim is to cut electricity price peaks, rather than to solve the power shortage during cold periods with little wind.

3.3 Electricity transmission

The supply of electricity is divided into electricity transmission in the main grid and electricity distribution in the distribution networks. Fingrid manages the main grid, and their dimensioning principles are that electricity must be transmitted sufficiently during peak load periods during extreme cold and that the network can withstand the failure of any individual plant (N-1 principle) without interruption of consumption or production. Fingrid aims for the N-2 level when the cost is not unreasonable.

The need to strengthen the main grid comes from the fact that electricity production is generally increasing in the north while consumption is increasing in the south. The decrease in flexible production has also been concentrated in the south. Fingrid estimates that 1GW of new consumption in southern Finland will, in practice, require a new 400kV line with an investment level of EUR 300–500 million.[25] This includes substations and compensation solutions on the main grid side. A 400 kV underground cable will be needed at some key points. Underground cabling in the urban environment costs around EUR 100 million in the Helsinki example.[26] Let's assume that one of these projects is needed for every 1 500 MW increase in consumption.

According to Chapter 3, the electricity system needs to be reinforced by 7 500 MW. The need to reinforce the electrical transmission system would not necessarily be this large in our scenario. Some of the consumption is located close to wind production. In our dimensioned situation, the peak production required can also be located close to consumption, which reduces the need to reinforce the transmission network. On the other hand, when the heating system is also switched to use wind power, the N-1 principle and the need for balancing inertia and other things increase the need for reinforcement considerably. We do not have the modelling capability to determine what the actual need would be. We use the 7 500 MW level in our calculations. When rough rules of thumb are used with large changes in the system, significant uncertainty is introduced into the cost estimates. However, we have tried our best to ensure that the estimate accurately reflects the size of the investment.

Table 5. Cost estimate for reinforcing the main grid.

Cost item	Cost assumption	Total estimate for 7.5 GW
400 kV north-south-transmission	EUR 300–500 million/GW	EUR 2.2–3.8 billion
Urban cabling	EUR 100 million per project	EUR 0.5 billion
Total		**EUR 2.7–4.3 billion**

[25] Impact Assessment of the Connection Fee Reform of Finnish Main Grid

[26] The Helsinki 400 kilovolt power cable connection

Reinforcing the grid would therefore cost, according to our estimate, 3.5 billion per 7.5 GW, or approximately EUR 0.47 million/MW.

In recent years, the strong growth in wind power production, concentrated on the west coast, and the consumption of surplus electricity, concentrated in the south, are placing a heavy load on the grid, even on windy, mild days. This has created a need to limit wind power production. This challenges Fingrid's traditional investment principles. Is it worth building the grid to also enable the consumption of surplus electricity at any time? If not, how can we manage a situation where wind power overproduction is balanced, but electricity transmission capacity runs out?

Surplus electricity gets consumed because of its cheap price. Taken to the extreme, the principle that the grid should not be allowed to restrict the flow of electricity under any circumstances could require that new grid connections be built just to utilize surplus electricity.

It is challenging and important to find cost-based pricing for these situations. In the electricity grid, consumption does not cause any variable costs other than losses, which are approximately 2% of Finland's electricity consumption.[27] However, investments and requirements for security of supply are high. Once the capacity of the components in the electrical grid is reached, even a small increase in demand would result in a large investment need. If there are several power situations to be dimensioned, for example a cold winter weekday and a windy mild winter day, simple power-based pricing does not work. In freezing temperatures, electricity output is based on a need that cannot be easily avoided. On a windy day, electricity output is not based on a need, but on the possibility of utilizing surplus electricity.

Fingrid is developing a transmission management marketplace to meet the challenges of managing transmission in the main grid. In this development project, which runs from 2025–2027, flexibility for managing both the transmission and distribution networks will be procured through a shared marketplace, in collaboration with Helen Sähköverkko. The marketplace will trade in flexible capacity and flexible energy.[28] The project aims to develop economic control methods for managing transmissions.

In district heating, the peak outputs of city heating cannot rely solely on electricity. Meeting the need for peak power with electric boilers would require fossil-fuel-based peak electricity generation and investments in power transmission lines, which might be needed for only a few days each year. The flexibility of district heating operators and non-electricity-based production capacity enable Fingrid to optimize transmission line investments in accordance with a reasonable peak usage period. Heat production alternatives improve supply security in district heating and also for other electricity customers. The system could be supported, for example, by agreements to reduce electric boiler use in disruption situations. This would reduce the need for investment in reserve transmission capacity.

3.4 Electricity distribution

New components that utilize surplus electricity in the distribution network are also challenging the existing operating models. Many electric boilers have been rapidly built for district heating production. In addition to these, more data centres and electrolyzers for hydrogen production are coming to cities. At the low-voltage level, electric cars and household batteries are loading individual transformer circuits. Electricity consumption in Finland has not increased in 20 years. Now, suddenly, electrical power is growing rapidly with new types of individual consumption points.

Mäki-Turja's master's thesis found that an increase in peak power of 87 MW would result in an investment need of approximately EUR 28.1 million. The estimated uncertainty range is EUR 18–34 million. The unit price used is EUR 28.1 million/87 MW = EUR 0.32 million/MW. This means that an increase in power demand of 464 MW in Tampere would result in an investment need of EUR 150 million and an increase in power demand of 7 500 MW in Finland would result in an investment need of EUR 2.4 billion.

[27] Häviösähkö

[28] Siirtojenhallinnan markkinapaikka käyttöön

Table 6. Network components to be built into the distribution network and their investment costs.[29]

LV-network	AX185 / AX300 average	14 099 m	26 € /m	366 375 €
	City centre installation	937 m	150 € /m	140 550 €
	Urban installation	6 704 m	120 € /m	804 443 €
	Distribution cabinet	723 pcs	10 000 € /pcs	7 230 000 €
Transformers	Substations and transformers average	145 pcs	33 170 € /pcs	4 809 700 €
MV-network	MV-cable	12 346 m	40 € /m	493 840 €
	City centre installation	0	150 € /m	- €
	Urban installation	4 445 m	120 € /m	533 400 €
	MV-output feeders	8 pcs	40 000 € /pcs	320 000 €
Substations	Power transformer	2 pcs	2 000 000 € /pcs	4 000 000 €
HV- network	Network reinforcement			9 410 000 €
Total				**28 108 308 €**

This cost estimate obtained through simulations is quite favourable compared to the replacement value of the networks. The peak electricity consumption in distribution networks in 2024 was 10 500 MW.[30] In 2021, the replacement value of distribution networks was EUR 19 billion.[31] This results in a replacement value of EUR 1.8 million/MW. If reinforcing the network costs the same as rebuilding, an increase in power demand of 7 500 MW would result in an investment need of EUR 13.5 billion. This is more than five times the estimate based on Mäki-Turja's analysis. In a dense network area like Tampere, electricity has many routes to travel, and strengthening a weak point in the network effectively utilizes the free capacity of the surrounding lines. Since district heating networks are concentrated in urban areas, we assume that Mäki-Turja's master's thesis describes the cost level better than the replacement value of electricity networks. Reinforcing the electricity network is many times more cost-effective than building a completely new one.

In our previous study, we used the higher power demand estimate according to model 1 presented in chapter 3.1. At that time, we also estimated the unit price of the ground-source transition in the distribution network to be approximately 22% higher than our current knowledge. At that time, we estimated the cost in Tampere to be approximately EUR 280 million. Now, with the updated figures, the cost in Tampere is approximately EUR 150 million.

If district heating production was stopped, the electrical power previously used by electric boilers would be freed up for electricity transmission elsewhere. This would not reduce costs much, since the dimensioning principle is based on the transmission demand in the event of an electricity shortage. In this dimensioned situation, electric boilers would not be in use. After a transition to ground-source heat, data centres and hydrogen production plants located in Tampere would also consume almost as much electricity as before. Their waste heat would simply not be utilized.

3.5 Scenario summary

Forecasting the entire energy system until 2040 is such a complex challenge in terms of market dynamics and politics that we do not present precise forecasts for 2040. Our analysis does not take a position on whether the electricity system can be combustion-free if district heating systems are maintained. However, we do observe from the scenario that if district heating is abandoned,

[29] Siiri Mäki-Turja, Maalämpökerrostalojen vaikutukset sähkönjakeluverkkoon, diplomityö, Tampereen yliopisto, Automaatiotekniikan DI-ohjelma, 2025.

[30] https://data.fingrid.fi/data?datasets=363

[31] Sähkön jakeluverkonhaltijoiden rakennetietojen raportointi Energiavirastolle

a combustion-free ground-source heating system does not seem plausible with current technologies.

The table below summarizes the results of Chapter 3. The transition from district heating to ground-source heating would cost approximately EUR 42 billion if peak power is produced with gas turbines. A combustion-free system would cost at least EUR 91 billion. The EUR 55 billion investment cost for batteries would require that the current cost level should fall by a third. At the current cost level, the investment would therefore be EUR 154 billion in batteries alone.

Table 7. The investment costs of transitioning to an electricity-based heating system in Finland. The table only gives the investment costs, which distorts the comparison slightly in favour of combustion.

	Power	Investment
Geothermal systems	14 500 MWth 7 500 MWe	€ 22,6 billion
Windpower	5 100 MWe	€ 7,1 billion
Peak production	4 600 MWe 550 GWh	Electric battery € 55–154 billion OR Gas turbine € 6 billion
Electricity transmission	7 500 MWe	€ 3,5 billion
Electricity distribution	7 500 MWe	€ 2,4 billion
Total		**€ 42–189 billion**

Table 8. The investment costs of transitioning to an electric-based heating system in Tampere.

	Power	Investment
Ground-source systems	900 MWth	€ 1,4 billion
	466 MWe	
Wind power Peak production	317 MWe 286 MWe 34 GWh	€ 0.4 billion Electric battery € 3.4–9.6 billion OR Gas turbine € 0.4 billion
Electricity transmission	466 MWe	€ 0.2 billion
Electricity distribution	466 MWe	€ 0.15 billion
Total		**€ 2.6–11.7 billion**

Unless the operating environment changes significantly in the next ten years, the need for electricity during a cold, windless week would have to be met with gas turbines. However, the emission impact of this would be moderate. Emissions from burning fossil gas in standby power plants would be an estimated 55 000 tonnes per year in Finland. Scaled to Tampere, this would be 3 400 tonnes. Emissions could be reduced further by using renewable and synthetic gases. There is no completely harmless energy production. In a ground-source system, a large part of the emissions would come from drilling holes, manufacturing pump systems, felling forests under the electricity transmission network, etc. Similar life cycle emissions are also generated by district heating systems.

Our comparison between district heating and ground-source systems is not primarily based on emissions, but on costs and lost opportunities for carbon dioxide capture. The scenario analyses in Chapter 3 show that if combustion is not allowed in the energy system, peak power generation in the district heating system is more cost-effective. If combustion is allowed, power management is still more cost-effective in the district heating system. Electric heating is better only in the moving target scenario, where combustion is allowed in the electricity system but prohibited in the district heating system.

A more detailed comparison between the heating systems is presented in Chapter 6. There we find that in addition to lower costs, the district heating system enables emission reductions outside the energy sector. This possibility will be explored in more detail in the next chapter.

4 The sustainability of bioenergy

When we talk about carbon-negative district heating, i.e. the capture of bio-based carbon dioxide, the environmental impacts of bioenergy inevitably come up in the discussion. The sustainability aspects of bioenergy are strongly interlinked with the use of forests, although most bioenergy comes from side streams in the forest industry. Next, we will examine the valuation of different biomass feedstocks from an environmental perspective and the role of bio-energy in the emission balance of the land use sector, before moving on to an assessment of technological carbon sinks.

Bioenergy combined with carbon dioxide capture is seen as central in the IPCC's climate change mitigation scenarios and the IEA's net-zero scenarios. In our view, it is not necessary to reach zero with the use of bioenergy, but its environmental impacts must be critically examined. In order for the use of bioenergy to be sustainable, the risks of carbon sink and biodiversity loss must be minimized. This requires companies to have sustainable operating models in wood procurement and reporting on their sources. In the ideal situation, only wood that has no other use and whose collection has a low impact on nature and climate would be used.

If bioenergy is to be replaced by production that does not rely on combustion, it is necessary to know how stopping the use of bioenergy would lead to an improvement in the state of the environment or the emission balance of forests, assuming that the operating environment in the forest industry otherwise remains the same. When comparing alternatives for energy production and carbon sequestration technologies, the material and ecological value of wood and the value of carbon sequestration must be weighed in relation to the emissions, costs and security of supply of the replacement alternatives.

There are differences in the different biomass feedstocks both in terms of climate and nature. Forest industry side streams, such as sawdust and bark, or unprocessable wood, cause smaller negative impacts on nature and emissions than, for example, the burning of logs and pulpwood. The method used to examine different natural and climate impacts, such as the time span taken into consideration, is essential. There is no single best method for assessment, which makes valuing different feedstocks uniquely challenging. For forest chips, interesting research questions include how the environmental impacts of combustion-free production compare to the environmental impacts of other production options, and how the energy sector can most effectively optimize biodiversity and emission impact together.

4.1 Overview of the use of different biomass feedstocks in energy production

In the Nordic countries, wood is also used by combined heat and power generation and thermal power plants, in addition to the forest industry. Bioenergy is not the solution to Europe's green transition, but it is relevant locally.

Sustainability is supported by a sustainable forest industry and district heating networks that enable the cascading use of wood. Cascading use means that wood is always used for value-added purposes as much as possible. Logs should be used to produce sawn timber and pulpwood should be used to produce pulp. For now, there is no other commercial use for energy wood than energy, so when it is produced as a by-product of forestry, it is worth using it economically in heat production. In the future, the use of energy wood, for example as animal bedding or in construction, may expand, but the scale of these uses is small. It should also be noted that the distinction between energy wood and pulpwood is not clear, so some of the wood currently used as energy wood could also be a valid raw material for the paper and pulp industry.

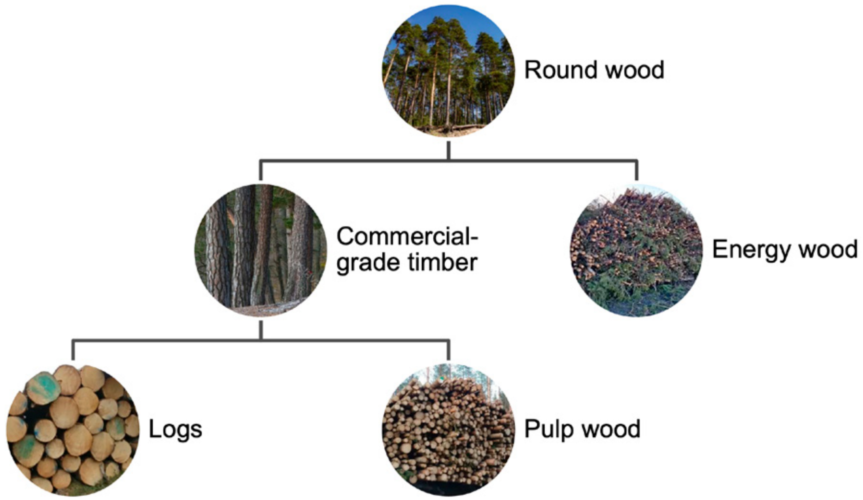


Figure 21. Raw wood classification.

When interpreting statistics, it is important to note that harvesting and using wood are two different things. The change in stocks between years can be significant in the statistics. In 2024, 4.9 million m^3 of energy wood was harvested from forests as forest chips (Figure 22). 0.8 million m^3 of chips was imported. Since 7.6 million m^3 of trunk and whole wood chips were used in total, the change in stocks plus the use of pulpwood was 1.9 million m^3 net. In addition to whole wood and trunk chips, by-products of forest thinning, 2.7 million m^3 of logging residues and 0.2 million m^3 of stumps, were used in energy production. A total of 11.5 million m^3 of forest industry by-products, pellets and recycled wood were also used in energy production.[32]

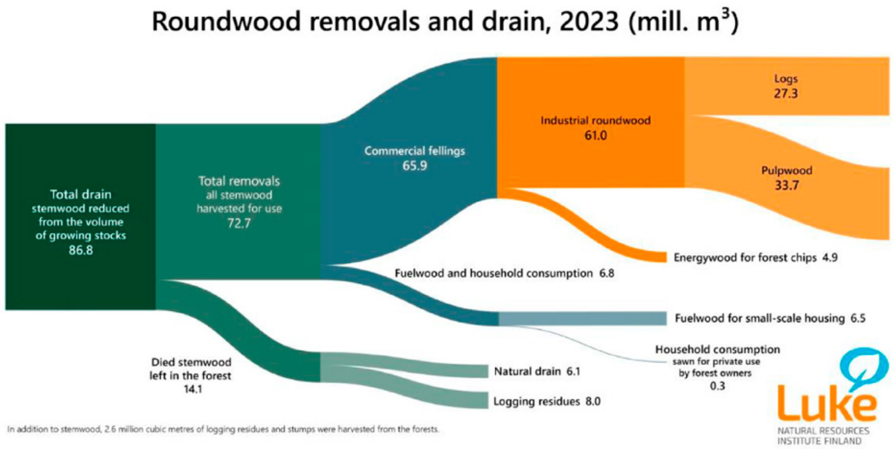


Figure 22. Round wood removal and felling in Finland in 2024 (million m3).[33]

The total use of solid wood fuel was 22.0 million m^3. Of this, the burning of pulpwood and stumps is not a viable use of wood. This accounted for approximately 10%. There are some exceptions when it is worth burning even more robust wood or stumps. For example, when a small number of trees and stumps of varying sizes are felled during construction, or the wood is not suitable for further processing due to quality defects. If we assume that there is no other economically viable use for the wood used for bioenergy, the use of energy wood should be reduced or sustainable imports should be increased by roughly 2 million m^3, so that energy use can be covered with fractions that are not suitable for processing.

During the energy crisis caused by the Russian war of aggression, an exceptionally large amount of processable wood was used in Finland for urban heating. This was influenced by both the decrease in the use of peat and the end of imports of Russian wood. The significant reduction in peat use has been the right decision from an environmental perspective, but it has not supported the other pillars of the energy trilemma, namely security of supply and price stability. However, we see the situation returning to normal quickly. A large amount

[32] Puupolttoaineet Suomen energian tuotannossa

[33] Hakkuukertymä ja puuston poistuma alueittain 2024

of new electric heating capacity will be completed by the winter of 2025–2026, which will improve the sufficiency of sustainable bioenergy fractions in heat production.

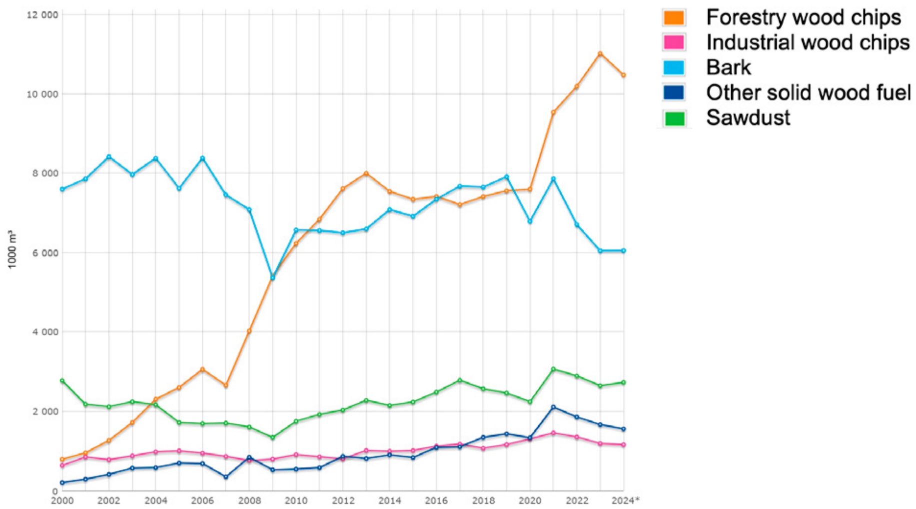


Figure 23. Use of solid wood fuels in heating and power plants by wood fuel.[34]

According to Figure 23, the amount of forest chips used has increased from 2020 to 2024 by about 3 m^3, that is, 6 TWh. At the same time, the use of peat has decreased by 5.5 TWh. Although the use of industrial roundwood and stumps must be phased out, it should also be noted that in the short term the alternatives would have been peat or fossil fuels. The emission impacts of these are greater than those of bioenergy, provided that bioenergy is not based on additional logging and the burning of saw logs.[35]

When Tampereen Energia adopted emission accounting in line with the GHG protocol in 2024, we examined the life cycle emissions of wood used for energy more closely (Kallio, 2025).[36] The sources of information available on life cycle emissions are inadequate for our needs and contradictory. The sources do agree that the emissions of secondary wood, i.e. industrial by-products, are low. They also agree that the emissions from saw logs are high. The emissions of bioenergy feedstock grown in fields, in turn, depends on the cultivation methods. However, the sources are not clear about what the emission factor for forest wood chips should be. Depending on the source of the emission factors and the chosen grouping of fuels, very different estimates are obtained for life cycle emissions. The range for the life cycle emissions of all fuels in 2023 was 35 000–60 000 tonnes of carbon dioxide. As a precaution, we have used the higher values in the range for our initial calculations, but further research is needed.

The biodiversity impacts of biomass are highly dependent on the raw material and procurement methods. Biomass based on side streams and small-diameter thinning wood causes significantly less impact on nature than biomass use that increases logging and, for example, reduces deadwood. Peat production, on the other hand, strongly degrades the ecosystems and species of the peatland. Of logging methods, clear-cutting causes significant climate and watercourse loads, especially if carried out in peatland forests. In peatland forests, disturbance of the soil surface should be minimised, while thinning wood from mineral soils does not cause a corresponding reduction in soil carbon stores.[37]

When comparing impacts on nature, there is therefore no straightforward answer as to which bio-based production method is better for biodiversity. The essential point is to seek solutions that reduce harmful biodiversity impacts along the chosen path and in practical implementation.

[34] Puun energiakäyttö 2023 | Luonnonvarakeskus

[35] Environmental sustainability - Bioenergy Review 2023

[36] Euroopan Unionin kestävyysraportointidirektiivin mukainen kasvihuonekaasupäästöjen laskenta: Soveltaminen suomalaiseen energiayhtiöön

[37] Näitä metsiä ei pitäisi avohakata – silti niin tehdään

4.2 Tampereen Energia's use of wood

For their district heat production, Tampereen Energia has shifted from natural gas and peat to electricity, waste heat and bioenergy. With the renewal of the Naistenlahti 3 bio-power plant, we have ended our use of peat. The use of bioenergy is currently at the same level as the company's combined use of peat and wood before the investments were made. At Naistenlahti, both electricity and heat are produced from October to May. In addition, bio-production capacity is available at the Hervanta wood-chip heating plant and the Sarankulma pellet heating plant, which are operated as required.

The need for biofuels is declining. Based on actual data and forecasts, it seems that 2023 will remain the peak year of use. Bioenergy has mostly been replaced by electricity. By the end of 2025, electric boiler capacity will have tripled, reducing the need for bioenergy. Although the use of bioenergy is decreasing, it plays an important role in stabilising heating costs, ensuring security of supply and reducing emissions from peak electricity generation.

Energy wood typically comes from small-diameter fractions. However, logs of higher quality also end up in energy production when, for one reason or another, they cannot be utilised elsewhere. These may be, for example, spruces damaged by bark beetles or trees with growth defects. In addition to this kind of energy wood, in Tampere we also utilise by-products of the forest industry in energy production, such as sawdust, bark, pellets and recycled wood.

The use of pulpwood for energy was exceptionally high in 2022–2024 in Tampere as well, due to the ending of peat use and the disruption in the timber market caused by the end of imports from Russia. However, the investments now made, will reduce the need for biofuels and bring flexibility to procurement. Tampereen Energia's responsibility programme includes new measures related to monitoring, reporting, certification, identifying impacts on nature and supporting cascade use of biofuels. At present, we are not aiming for zero use of bioenergy. Its role in the energy sector as an enabler of biogenic carbon dioxide capture and as way to stabilise electricity use will remain, albeit at lower volumes.

4.3 Technological and natural carbon sinks

The increase in the concentration of atmospheric carbon dioxide is a key driver of climate change. Overall, the world's forests and soils absorb about one-third of humanity's annual carbon dioxide emissions, while the oceans take up a little over one-quarter. In Europe, exceptionally hot weather and extensive forest fires have reduced soil and vegetation sinks to almost nothing. In Finland too, the land-use sector has now turned into a source of emissions.

Natural sinks provide an essential but vulnerable buffer in combating climate change. That is why the role of technological sinks will increase in the future. It is clear that regulation must first ensure that fossil carbon remains underground, and then invest in the permanent storage of carbon circulating in the atmosphere. If climate targets are to be achieved effectively, these measures must nevertheless be advanced simultaneously.

4.3.1 Emissions from the land-use sector

The land-use sector (LULUCF) is included in Finland's official greenhouse gas inventory as a separate sector. It covers forests, cropland, built-up land and changes in land-use. So far, Finland's national targets have considered emissions and sinks from the LULUCF sector as a separate thing, albeit as part of the overall climate target. The EU's 2030 target requires that Finland's land-use sector to absorb more carbon than it emits.

The change of the land-use sector from a sink to a source of emissions (figure 24) is the result of many factors. Forest growth shows that the period of rapid growth of forests heavily regenerated in the 1960s and 1970s is coming to an end. In past decades Finland had a lot of young forest in a high-growth phase, but now forest growth has slowed. In addition, advancing climate change weakens sinks as the net growth of tree stands declines. According to the National Forest Inventory, the average annual growth of tree stands fell by about 10% in the period 2019–2023 compared with the peak numbers of the

2010s.[38] The slowdown in growth has also been affected by longer dry spells, warm summers, storms and bark beetle damage. Emissions from drained peatlands have doubled over the past ten years, and they will soon become one of Finland's most significant individual sources of emissions. As the climate warms, these emissions will increase. [39]

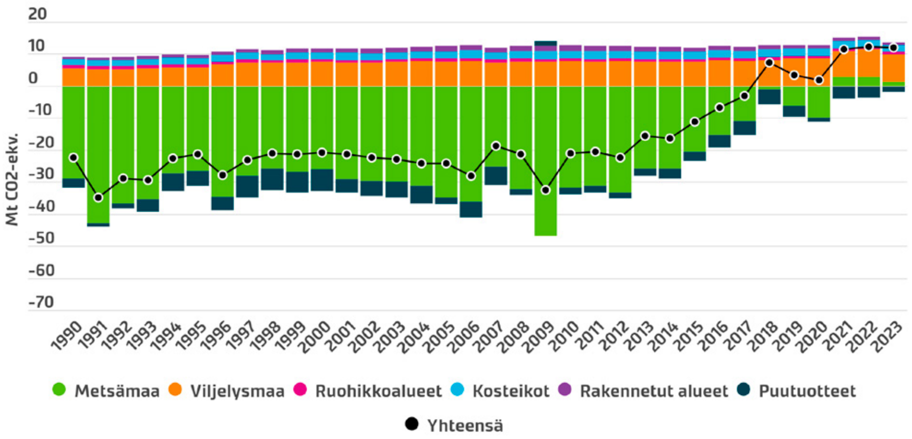


Figure 24. LULUCF sector emissions and removals by land use category. A positive number is an emission and a negative number is a removal.[40] The legend from left to right: Forest, Agricultural land, Grassland, Wetlands, Built-up areas, Wood products, Total.

In addition to the slowdown in forest growth, a significant reason for the decrease in the carbon sink has been the increase in logging. High logging rates weaken the carbon sink of forests. Economic logging reached record levels in 2018 (76Mm^3) and remained above average in 2021–2023 (73Mm^3 on average). It is possible to increase sinks in the short term by limiting logging. For example, reducing the logging rate by about ten percent would significantly contribute to the 2030 sink targets.[41]

According to Luke and the Climate Panel, limiting logging would be the fastest way to increase the sink, although logging is only part of the story with land use sector emissions. Soil emissions and the slowdown in tree growth are significant factors, but there are unfortunately few measures available to address these. Without controlling the logging rate, forest management measures and emission reductions from peat bogs are not enough. On the other hand, global warming threatens the carbon sink of forests, even if logging decreases, and therefore climate goals require diverse measures. The compensation capacity of the land use sector cannot be relied on.

Significant methodological changes have also been made to the calculation of the land use sector sink. Luke reported in January 2025 that simply recalibrating the calculation added 7.6 Mt to the net emissions in 2022.[42] The inventory calculation specified the soil emission factors and the calculation model. The effect did not change the actual amount that ended up in the atmosphere, but revealed previously underestimated emissions.[43]

The data from the 2023 greenhouse gas inventory revealed that if the calculation method is also corrected for the reference figures, compared to 2015, approximately 20% of the change is caused by the slowdown in tree growth, 40% comes from the increase in logging and the remaining 40% from the increase in soil emissions.

The primary reason that the land use sector has become an emissions source is the slowdown in tree growth (the age structure of the forests, drought and heat), high levels of logging, soil emissions and correction of the calculation method. Restoration simultaneously requires climate-resilient forest management, reliable monitoring and reduced logging. The market mechanism has proven to be a good control tool. High wood prices reduce demand and logging. But incentives, for example, for storing carbon in living forests through a voluntary carbon removal market can also provide a useful alternative for forest owners who are interested.

[38] Metsien rooli ilmastotavoitteiden saavuttamisessa

[39] Ojitetuista turvemetsistä tulossa pian selvästi suurin ilmastopäästölähde

[40] Kasvihuonekaasuinventaario 2023: maataloussektorin ja maankäyttösektorin lopulliset tulokset hyvin lähellä ennakkotuloksia

[41] Ilmastotavoitteiden saavuttaminen vaatii nopeita korjaavia toimia maankäyttösektorilla

[42] Forest land has turned into an emission source because the carbon sink of trees no longer cover emissions from forest soil

[43] Metsät ovat kääntyneet päästölähteeksi, koska puuston nielu ei enää riitä kattamaan metsien maaperän päästöjä

Maximizing carbon sequestration may conflict with maximizing biodiversity.[44] Focusing on only one leads to partial optimization. For example, fast-growing tree species maximize biomass production in the short term, but deplete the species composition and structural variation of habitats compared to natural forests. According to the IPCC analysis, strategies aimed at rapidly increasing the biomass stock can have harmful side effects on biodiversity. To the extent that the national carbon sink needs to be maximized, it is also advisable to promote the construction of a technical sink, which should be dimensioned by balancing the sink of the land use sector and the negative impact on nature.

4.3.2 Bio-based carbon capture

Achieving our climate goals requires carbon capture, either for use or for permanent storage, i.e. CCUS technologies (Carbon Capture and Utilization or Storage). These are not mutually exclusive options, but complementary solutions for combating climate change. The district heating system will play a significant role in Finland as an enabler of carbon capture technologies, as long as the obstacles in the current market and regulatory environment can be resolved.

In addition to the forest industry, bioenergy is one of the areas with the most potential to introduce bio-based carbon capture in Finland. However, Finland's current political will does not support this approach. Four enabling measures are needed to create carbon capture capacity:

1. A separate national target for carbon capture that clarifies the need beyond the electoral period.
2. Signs of a more stable regulatory environment, where the current problems are the legitimacy of wood use and the complex reporting rules for carbon capture and utilization.
3. Infrastructure, i.e. strategic pipeline and terminal investments.
4. Measures to improve profitability, such as national support mechanisms and creating value for stored carbon.

As a result of the September budget debate, the Finnish government reduced the mandate of the Clean Energy key project so that the appropriation will decrease by a total of EUR 90 million in 2027. Of the cut, EUR 40 million will be directed at support for large clean transition investments and EUR 50 million to support for carbon capture, leaving the support amount for carbon capture at EUR 90 million. Related to this cut, the government raised the issue of extending clean transition tax credits to carbon capture projects, but there is no further information on the timetable or other details about this measure. At the same time, the scenarios in the draft medium-term energy and climate strategy propose very significant capture capacities without sufficient measures to strengthen profitability.

The slow start of the technology in Finland has been explained by shortcomings in EU-level regulation even though, at the same time, projects have progressed further in planning in other Nordic countries. Finland's strategic guidelines state that if the regulatory framework does not progress, the promotion of the technology should also be assessed through standard guidance. In practice, we are competing for capture investments with countries where the technology is significantly supported by national subsidies. So far, the financial contributions in Sweden are more than 15 times larger and in Denmark more than 25 times larger than the planned subsidies in Finland, even though the carbon neutrality target in Sweden and Denmark is set for 2045, and in Finland for 2035. If the already unfavourable competitive situation is weakened further, the emergence of new business in Finland will become more difficult. Strong standard guidance or taxation for the lack of carbon dioxide capture will not lead to the introduction of technology, but will endanger the financial sustainability of companies and distort the heating market.

Finland's competitive advantages are cheap electricity, bio-based carbon dioxide point sources and the possibilities that district heating networks provide for utilising waste heat. The challenges, in turn, are low political pressure, lack of subsidies, the seasonal variation of carbon dioxide flows in district heating networks, and the lack of CO2 infrastructure and permanent storage. The forest industry does not have the same challenge with seasonal variation, so the role

[44] Agriculture, Forestry, and Other Land Uses (AFOLU)

of the forest industry in technical carbon capture in Finland will be significant in the future. On the other hand, the large point sources in the forest industry bring their own problems with capture technology and market scalability.

Finland's competitive advantages are cheap electricity, point sources of bio-based carbon dioxide and the possibilities for utilising waste heat brought by district heating networks. The challenges, in turn, are low political pressure, lack of subsidies, the seasonality of carbon dioxide flows in district heating networks, and the lack of CO2 infrastructure and permanent storage. The forest industry does not have the same challenge with seasonality, so the role of the forest industry in technical carbon capture in Finland will be significant in the future. On the other hand, the large point sources in the forest industry would bring their own problems with capture technology and market scalability.

Tampereen Energia currently sees potential for carbon capture particularly in CCU projects, because they create value for the district heating company through the natural function of utilizing waste heat, and the political risk from the project to the core business is therefore significantly lower.

Despite the challenges and uncertainties, Tampere already has a CCU project for the Tarastenjärvi utility power plant at an advanced stage, and another is planned for the Naistenlahti biopower plant. The Tarastenjärvi project progressed first because the plant has a longer operating time than Naistenlahti and there is more available land. Progress in Naistenlahti is currently limited by the plant's long seasonal maintenance and its location in the middle of a dense population.

We are taking a wait-and-see approach to carbon dioxide storage projects, as the infrastructure is still lacking and the demand for carbon removal certificates is only just taking shape. Although Tampereen Energia has a passive position on CCS at the moment, this does not mean that carbon negativity will not be possible in the district heating network by 2040, for example, if the price of emission rights increases or if technological carbon removal was included in emissions trading. When introducing technologies, a commitment will be made to a specific carbon dioxide use to get the projects started, but in the long term, capture equipment also enables a different carbon dioxide value chain, either for storage or for utilization.

Project profitability and demand

Carbon dioxide storage or recovery is not a technical problem, but an economic one. Support mechanisms alone are not enough; in the long term, a functioning EU-level market is needed. Carbon dioxide storage does not produce any value in principle, except to solve climate change. Therefore, projects are not profitable unless regulation forces a market to emerge. The same applies to carbon dioxide recovery projects. This requires faith from the project developer. If climate goals are compromised, the projects are unlikely to be implemented.

The polluter-pays principle has long been a cornerstone of environmental policy in Europe, implemented primarily through the EU emissions trading system. If emissions subject to emissions trading are captured and stored permanently, the operator avoids paying emissions rights fees for these. The proceeds from the emissions trading scheme will ultimately be channelled into green transition investments through the Innovation Fund, whereby higher-risk investments such as CCS will be financed with money raised from the production of emissions without general tax funds. On the way to net zero, there will inevitably come a point when some emissions are technically or economically difficult to avoid, and carbon capture and storage will become an essential part of industrial carbon management. This will require a cross-sectoral, risk- and cost-sharing policy. For example, the Norwegian Longship project has been built with significant state support specifically as an open European carbon transport and storage service, not as a private project of a single polluter.

According to studies by Tampereen Energia, the investment in full-scale carbon capture equipment for the Naistenlahti biopower plant has risen to EUR 400 million. The investment would be unprofitable in the absence of a market, even though bioenergy carbon capture (BECCS) is the most cost-effective solution for implementing a technological sink.

Tampereen Energia modelled the effects of connecting the Naistenlahti biopower plant's carbon capture to the power plant's energy balance (Paananen, 2025).[45] Electricity consumption is the largest cost item in the operating costs

[45] Hiilidioksidin talteenottolaitteiston lämmöntalteenoton vaikutus voimalaitoksen toimintaan

of carbon capture, as carbon capture and compression consume approximately 17–18% of the plant's fuel power. The plant's net electricity production without capture is approximately 22% of the fuel power, while with capture it would only be approximately 2%. Although electricity consumption is high, the recovery of waste heat from the capture equipment significantly increases district heating production and improves the overall efficiency and profitability, calculated based on the plant's fuel efficiency. The key to profitability is the ability to optimise electricity consumption so that projects do not weaken the state of the electricity system during peak consumption situations.

According to the Climate Neutral Tampere 2030 roadmap, the city's carbon neutrality goal will be achieved by reducing emissions by 80% and compensating the remaining 20%. In Tampere, the Naistenlahti 3 biopower plant has a carbon dioxide capture potential of approximately 0.4 Mt, which is above the set offsetting target. The city's climate goals can therefore be achieved with BECCS technology. In addition, the introduction of the technology would have positive effects on the regional economy. However, at current price levels, the purchase of CDRs (Carbon Dioxide Removal) would burden the city's economy by tens of millions annually, which is difficult to justify in a tight economic situation.

Looking at the low profitability of the projects, it is contradictory that the EU's emission target requires a huge need for bio-based carbon dioxide, around 20–30 Mt in the transport sector alone by 2030 and over 400 Mt by 2050.[46] CDR demand forecasts vary, but are undoubtedly over 100 Mt by 2030. These amounts are not realistic considering the availability of bio-based carbon dioxide in Europe. Point sources produce around 25 Mt of bio-based carbon dioxide in Finland and around 200 Mt in Europe.[47] Although growth is expected for smaller sources of carbon dioxide, such as biogas plants, the estimated maximum potential of these is also insufficient, around 89 Mt in 2040.[48] The carbon dioxide demand derived from climate targets is roughly four times the availability of bio-based carbon dioxide, so many other technologies are also needed. However, projects that could capture even a fraction of the tons of carbon dioxide required by the emission targets are not progressing. This is because of the high price of these products and because the demand is being created by binding legislation, whose permanence is uncertain. Demand for CCU is growing via synthetic fuel distribution obligations. Finland's high target for European green hydrogen production (10%) has increased their potential, but on the other hand, the minimum obligation for synthetic fuels in the distribution obligation has been lowered, which weakens the demand outlook. Demand for CCS, in turn, is growing so that carbon neutrality targets are creating demand for carbon removal certificates. The emission targets have indeed been set, but there is no legislation or functioning market for the technological carbon removal needed to achieve these targets that would encourage companies to invest. The EU itself should create the need for investment through regulations that put pressure on energy users and industry – this is not popular in all member states. The measure that could most likely increase demand for CCS in the EU is the inclusion of technological sinks in emissions trading. However, the price of emission rights would have to triple from the current level for this measure to make such projects profitable.

Of course, the EU Carbon Removal Certification Framework (CRCF), adopted in November 2024, creates a voluntary, EU-wide standard for permanent technological sinks. The key regulation for carbon dioxide recovery is the RFNBO Directive. However, project developers cannot rely on these regulatory frameworks to lead directly to economic incentives or long-term demand, although they ease quality assessment of the technologies. On the other hand, strict quality assessments complicate regulation and increase project costs. In addition to these regulations, the operating conditions for carbon dioxide capture will be improved by the carbon dioxide infrastructure regulation package being developed in the EU.

In the current geopolitical and economic context, the EU is balancing between implementing the necessary regulations to meet its emissions targets, which could undermine competitiveness, or relaxing the targets. Other continents, especially Asia, have seen positive progress in legislation and financing for carbon capture. In the Americas, on the other hand, progress has been driven by projects linked to natural gas processing and oil production efficiency, where the profitability and motivation of the projects are, in part, different from those in Europe.

[46] Why an e-fuel mandate for ships?

[47] Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe

[48] Biogenic CO_2 from biogases: key to Europe's carbon strategy

Carbon capture emissions accounting

The uncertainty around the rights to use emission reductions and reporting rules also hinder carbon capture projects. Preventing double counting, i.e. multiple parties reporting the same emission reduction as their own, is important, but it must also be understood that projects will not start unless all the parties that have invested in the project benefit from it. The first projects rely on both national subsidies and the risk-taking capacity of pioneering companies, and this must be taken into account in emissions accounting for the benefit of both the state and the company.

Emission reductions generated by the recovery of bio-based carbon dioxide are viewed as national emission reductions in Finland if a product made from carbon dioxide, for example synthetic fuel, is used in Finland to replace fossil fuels. However, carbon dioxide is still considered to be an emission of the power plant and energy company that produced it, even if the carbon dioxide is captured and only released into the air by the transport sector. A district heating company therefore will not receive any emission reduction benefit from carbon dioxide capture and the feasibility of the project depends on the utilization of waste heat.

The prevailing practice in emissions accounting for permanent carbon dioxide storage is that the storage of carbon dioxide is recorded in the national emissions balance of the country where the removal occurs. If a country wants to transfer emission reductions to another country, the mechanism of Article 6 of the Paris Agreement must be used. In this case, the country that removed the carbon must add a corresponding entry to its own accounts.

Certification agreements in voluntary carbon offset markets are typically concluded without this kind of Article 6 authorization. In these cases, the removal remains in the balance sheet of the country of origin, but the purchasing company can record the removals in their own net zero calculations. This overlapping record should not be considered double counting, because national and company-level inventories are different systems. This practice is used in all projects for European structures. With the Stockholm project, for example, the European Commission viewed the financial cooperation between the public and private sectors positively, and the double claims were not seen as problematic.

Some standards (e.g. SBTi) accept this practice. However, some organizations and member states have expressed concerns about how this could make assessment of the effectiveness of climate action less clear. According to some actors, additionality will not be achieved if removals are seen in two places (the state and the company), which critics say endangers the EU's climate leadership. However, climate leadership is more likely to be hindered by incentives that are unclear and too weak, especially since the quality of removals has already been addressed within the EU certification framework.

Combating climate change in Europe requires CCUS solutions, in which district heating will be a key enabler. In Finland, CCU is progressing faster than CCS thanks to the clear business model. A breakthrough in technologies will require, among other things, national targets, investment support and measures to build carbon dioxide infrastructure.

4.3.3 Other carbon dioxide storage methods

In addition to BECCS, many other technologies are being developed for carbon dioxide capture and sequestration, which are at different levels of maturity. In addition to point-based capture, direct air capture (DACCS) has also progressed, and there are several operational plants worldwide. Technologies like mineralization, for example, in which carbon dioxide is sequestered into calcium or magnesium carbonates, have a lower level of technological maturity. The advantages here is the permanence of the storage and low risk of leakage, but the challenge is the high energy requirement. According to several comparisons, BECCS is the most cost-effective of the large-scale carbon sequestration technologies,[49, 50] so we see the study of these low-maturity technologies as too speculative to be included more extensively in this study.

[49] The role of Direct Air Capture technologies in the EU's decarbonisation effort

[50] Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies

Solid biomass storage

A technology comparable to the development of a technical carbon sink is solid biomass storage, which also removes circulating carbon from the atmosphere. Long-term storage of carbon in solid biomass can be more cost-effective than gaseous storage. When implemented correctly, it is permanent and scalable. The most important solid storage technologies are the storage of living trees in forests, the production of biochar, the storage of wood in peatlands, for example, and long-lived wood products.

Forest carbon stock

The term "forest carbon stock" refers to all the carbon bound in a forest, which includes the carbon in tree trunks, branches, leaves, roots, as well as in the soil and litter. It acts as a "carbon bank" for the forest, and it grows as the forest grows and remains stable unless the forest's condition changes significantly. The term "carbon sink", in turn, describes how a forest binds atmospheric carbon dioxide through photosynthesis and increases its carbon stock. A growing forest is an effective carbon sink, but an older, slower-growing forest is more of a carbon stock.

Forest growth, and thus carbon sequestration, is greatest in forests that are managed well at the right time. As a result of good forest management, trees increase their growth in the short term and become stronger, but of course different tree species react to thinning differently. When trees are felled, the forest's carbon sequestration rate declines for a while until the forest reaches a rapid growth phase. Eventually, growth slows down again as the forest ages. Thinning forests according to recommendations maintains their vitality, but the number of fellings could be reduced (see Chapter 4.3.1). Old and natural forests play a significant role as carbon stocks and safeguard biodiversity.[51]

If a carbon stock was established in a forest and then commercialized, there would still be challenges, for example, how to deal with forest fires or forest destruction. We would have to consider things like whether the carbon is permanently stored in the forest? Would a forest owner have to pay emissions fees for the carbon dioxide released by a fire? Forest fires and other forest destruction are a natural part of the forest cycle. They release carbon into the atmosphere in the same way as human exploitation.

If a growing forest receives cash flow from the sequestered carbon, would it be worthwhile to afforest fields as a wood reserve, and how would this, in turn, affect the national food supply? In this case, the question is what is the value of carbon sequestration in the forest compared to the value of different wood fractions in industry.

Biochar

Biochar is produced by heating biomass in oxygen-free conditions, which produces carbon that decomposes very slowly in nature. The carbon contained in biochar remains in the soil for up to thousands of years. Biochar can be used, for example, to improve the soil's ability to bind nutrients and water, which makes farming more efficient and prevents erosion, or in construction products such as concrete and asphalt. Biochar can be produced from the same raw material that is currently used for bioenergy. On the negative side, the refining process requires expensive investments.

The cash flows generated by biochar and its by-products (e.g. heat) must be sufficient to cover the investment costs in order to justify the integration of biochar into the forest utilization value chain. For now, the demand for biochar as a product is limited by its relatively high price and the seasonal nature of the need. One possibility is to try to support increased biochar production initially from the perspective of heat production and carbon sequestration, and take the risk that the demand for biochar will grow.

Biochar is one of the most promising and feasible technological carbon sink solutions. Biochar meets the requirements of the EU Carbon Removal Certifi-

[51] The role of Direct Air Capture technologies in the EU's decarbonisation effort

cation Framework and is officially recognized as a technological carbon sink. There are currently six biochar plants in Finland and there is growing interest in new plants. The advantage of biochar is lower costs, but its scalability for large volumes is completely inadequate. Another challenge is the regulation of the final storage of biochar. Biochar would be profitable to add to agricultural land, for example, where its moisture storage and microbial substrate would increase growth. However, the issue of how to monitor carbon persistence is still unresolved.

Wood storage

One of the more speculative solid biomass storage technologies is underground wood storage, also studied under the name Wood Harvesting and Storage (WHS). In this, felled or fallen wood is collected and stored in oxygen-free conditions so that it does not decompose and the carbon is stored. However, the technology is not widely used globally, unlike the other technologies mentioned above. The aim of this section is to highlight a carbon sequestration solution that is less directly suited to the current energy system, as in the long term in the future we may also have to think about more creative ways to remove carbon dioxide from the atmosphere.

Wood has a good shelf life in oxygen-free conditions. Archaeological excavations have found wood that has been preserved for millions of years. However, preservation is affected by climatic conditions, which could be a challenge in the case of Finland. Wood storage technology has been developed for dry environments, where biomass does not decompose as easily as in the more humid Finnish terrain.

Zeng and Hausmann present seven different types of wood storage, of which the simplest to implement in Finland would be a one-hectare wood storage that is 5 meters deep and 20 metres high, which can store 100 000 m^3 of wood (Figure 25). [52]

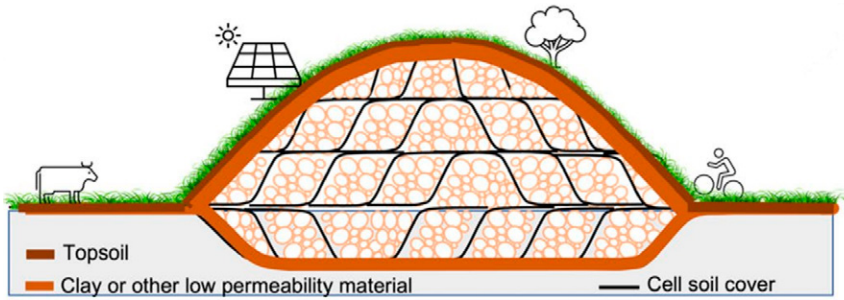


Figure 25. Diagram of a wood vault for carbon storage.

The space and costs required by a wood vault are reasonable. The theoretical potential for carbon sequestration in Finland, if all pulpwood and smaller biomass were stored, would be approximately 51 Mt CO_2 per year. In this case, the space requirement would be 0.17% of the area of Finland in a hundred years, and the area could still be used for many purposes. At current wood prices, the cost would be just over EUR 100/t, while the BECCS storage price reference is approximately double (>EUR 200/t). At the theoretical maximum, considerable additional costs would arise from the loss of income for the forest industry.

Burying wood has no other benefit than slowing down climate change. As long as, for example, coal continues to be mined, storing carbon or carbon dioxide will just be an expensive way to compensate for the use of coal elsewhere. However, on the path to net zero, it is necessary to promote various carbon sequestration technologies simultaneously at the same time as fossil fuel use is phased out, to accelerate the transition and achieve national climate commitments.

It would be relatively easy to rank the costs of different types of climate action if there were a global system in place to manage to the carbon cycle. A smart planner would first want regulations that would keep coal underground, followed by measures to store carbon circulating in the atmosphere. However, this is not the case, highlighting the challenges of current international cooperation.

[52] Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future

5 Technologies

This report evaluates various non-combustion or carbon-negative heat production technologies from three perspectives: potential, cost and availability. The primary goal of this classification is to open up the dimensions of the "goodness" of the technologies so that they can be addressed in further discussions. Criticising a technology's emission reduction potential and its price are two different things. A slightly high cost is not an insurmountable obstacle; emission reductions always have a price.

We have strived for objectivity in these figures, but with such a complex subject, they realistically say more about Tampereen Energia's current situation, on which we base our decisions. The authors are open to challenges about these findings.

Emission reduction potential refers to the emission impact of the technology if the technology were to be widely adopted. For example, a city-sized energy storage facility does not reduce emissions at all by itself, but it enables more efficient use of other technologies. Similarly, if the technology only provides heat in the summer, its emission reduction potential is small. Heating a city in a zero-emissions manner in the summer is not difficult.

Emission reduction potential:
4 = could solve the problem of carbon-neutral heating alone
3 = high
2 = moderate
1 = low

Costs refer to the total investment and operating costs. Making an estimate is challenging because the current costs and costs in ten years' time will be different. The aim of the study is to increase understanding of the obstacles to the transition to a carbon-negative society today. The cost level today is a more relevant reference level than the speculative cost level in the future. Some hypothetical technologies have been examined in the work, because it is important to clarify why solutions cannot be based on them in light of current knowledge.

Costs:
4 = enables the price of district heating to be reduced
3 = enables the price of district heating to be kept unchanged
2 = forces the price of district heating to be increased
1 = significantly more expensive than customers' alternative heating methods

Availability refers to Tampereen Energia's ability to influence the adoption of a technology. If the solution cannot be obtained from anywhere, and Tampereen Energia cannot significantly promote the adoption of the technology through its own actions, it gets a rating of 1 for availability. If the technology receives a rating of 1 in any category, it is not considered further in this report. We will continue to monitor different technologies and update our assessment of the maturity of the various alternatives.

Availability:
4 = Tampereen Energia can decide to acquire it by itself
3 = requires approval from a partner
2 = requires approval from multiple stakeholders
1 = at the idea stage

Table 9 review of technology maturity

Technology	Emission reduction potential	Cost-effectiveness	Availability
Heat storage	3	3	4
Electric boiler	2	4	4
Waste heat	3	4	4
Hydrogen heating	2	1	2
Air-to-water heat pump	2	3	4
Geothermal heating	3	1	2
Small nuclear reactors	4	3	2
Solar heat	1	1	4
Demand-side flexibility	1	3	4
Carbon dioxide capture (CCS)	4	2	2

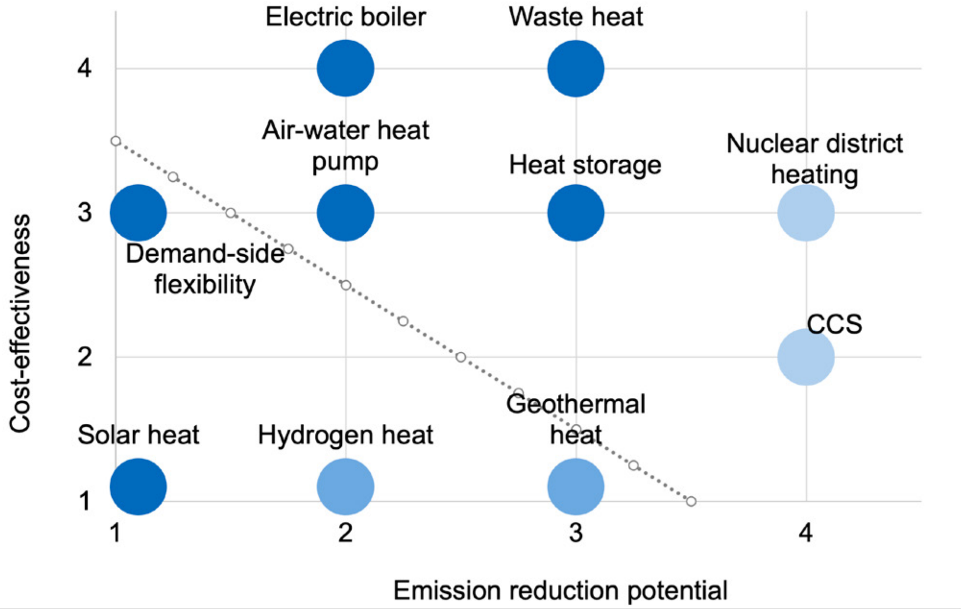


Figure 26. Summary of the potential, cost-effectiveness and availability of technologies. The lighter the circle, the lower its availability. The most interesting technologies are the circles in the upper right corner. The dotted line on the graph indicates the limit below which technologies are not interesting enough to be considered in our scenarios.

5.1 Thermal storage

- **Emission reduction potential = 3**
- **Cost-effectiveness = 3**
- **Availability = 4**

The thermal storage does not produce energy or power in itself, but enables other solutions to be connected to the heating system and the storage of electricity as heat. Depending on its size, thermal storage can be used for three different purposes: intraday use, weekly use and seasonal storage. In addition, in practice, demand-side flexibility works like intraday thermal storage.

Storage is a particularly attractive option when heat is produced from electricity. The price of electricity varies greatly, so shifting production within a day or week is profitable. In the electricity market, the price is also a good indication of zero emissions. Since the current high price of emission rights increases the production cost of fossil electricity, it can be said that when the market price of electricity on the electricity exchange is low, it is also very low-emission.

A good solution for intraday storage is a traditional insulated steel tank in which heat is stored in water. In this solution, heat losses are negligible and the controllability is good, so even a relatively small storage unit can be very useful. The benefits are particularly significant in spring and autumn, when the temperature difference between night and day is large. In Tampere, the size of the heat storage units is between 100 and 2 000 MWh. Their cost-effectiveness is high, but their maximum potential for covering a cold week is small. A heat storage unit of approximately 800 MWh was completed in Tampere together with our electric boilers during 2025.

Heating demand-side flexibility

Demand-side flexibility also works for intraday management. In this context, heat demand-side flexibility refers to the transfer of consumption from one hour to the next, not energy savings. With demand-side flexibility, buildings are left unheated for a moment, and the heating need is postponed to a moment when heating can be done more cheaply and with lower emissions. However, a building cannot be left cold for many days and the building temperature must be returned to normal relatively quickly. According to a Ruohola study (2021), the duration of heating flexibility for customers of a district heating company with 100% heating capacity flexibility is approximately 5–12 hours.[53] Of course, heat demand-side flexibility can be implemented for longer than this in premises that are not used for residential purposes, such as warehouses, but there are so few of these that the effectiveness of such solutions on the scale of city heating is negligible.

If the district heating system already has district heating thermal storage, demand-side flexibility will only provide a small benefit in intraday management. District heating thermal storage reduces the annual cost savings of demand-side flexibility by about 90% compared to a system with demand-side flexibility but no district heating thermal storage. District heating thermal storage is already sufficient to smooth out intraday peaks, after which the short-term flexibility created by demand-side flexibility is only very rarely useful. The cost of installing control devices in thousands of properties would also be a considerable cost. Similarly, controlling them securely and in a way that the indoor conditions of the buildings do not deteriorate too much compared to the small cost savings achieved would be a difficult challenge to solve. Starting up a heating plant for backup power only costs some hundreds of euros, so the cost savings of additional starts would only be a few cents per customer.

The potential for emission reductions from demand-side flexibility is therefore good in some networks, but very small in the case of Tampere. The reason that smart heating solutions have great potential to reduce emissions is that

[53] Lämpöyhtiön kysyntäjoustoon pohjautuvan energiatehokkuustuotteen ja sen kannattavuuden arviointi Lämpöyhtiön kysyntäjoustoon pohjautuvan energiatehokkuustuotteen ja sen kannattavuuden arviointi

they provide a tool to lower indoor temperatures in a controlled manner, which directly affects a building's energy consumption. Simply adjusting the indoor temperature up or down is much less significant in terms of energy savings, both in terms of the customer's energy bill and in terms of emissions from the district heating network. It is better to balance demand fluctuations in the district heating network centrally rather than by worsening the conditions for all customers, because power management in the district heating network is cheaper. Thermal storage and demand-side flexibility together are a belt and braces-style solution: you need both to make them useful.

Seasonal thermal storage

Weekly storage requires a significantly larger storage capacity, for example, 10 GWh or more in Tampere. This kind of storage facilities have been built, for example, in Oulu (Laanila, 1999, 8 GWh), Helsinki (Mustikkamaa, 2021, 12 GWh) and Vaasa (Vaskiluoto, 2020, 11 GWh). Heat can be extracted from a 10 GWh thermal storage facility for a week, for example, with an output of approximately 60 MW. 60 MW corresponds to a maximum of 20% of Tampere's current district heating needs even in the warmest moments of winter, so seasonal storage cannot be considered. All weekly storage facilities built to date have been built in old oil caves. In solutions of this scale, heat losses constitute a significant cost, because it is not economical to insulate the thermal storage facility.

Finland's district heating thermal storage systems are large even by European standards. By the end of 2024, 61 GWh of electric batteries had been installed across Europe.[54] By the end of 2023, 39 GWh of district heating thermal storage had been installed in Finland. [55]

It is technically possible to build an estimated 10–16 GWh of unpressurized or low-pressure thermal storage in Tampereen Energia's oil storage. According to the definition found in the introduction to the chapter, the cost-effectiveness of such a storage depends on the amount of electrification in the system. In a fully electrified system, the cost-effectiveness of weekly storage is either 3 or 4 on a scale of 1–4, in the current system it is more likely 2 or 3, as the profitability of thermal storage is based on the availability and price of the form of energy production that replenishes it.

New solutions are also emerging alongside these traditional types of thermal storage. If implemented, the Kulomäki pit thermal energy storage facility in Hyvinkää would be the first of its kind in Finland: the former gravel pit will be lined with plastic film, filled with water and covered with a floating, insulated cover; It can store approximately 20 GWh of 90°C heat with a single charge, and the project is estimated to cost approximately EUR 20 million. Technically, the pit will operate atmospheric pressure at ground level, so the construction will mainly involve earthwork and insulation work, while traditional rock storage facilities which use converted oil caves are situated tens of metres down, and require rock excavation and a pressurized water circuit.

Figure 27. The pit thermal energy storage facility in Hyvinkäää.[56]

[54] European Market Outlook for Battery Storage 2025-2029

[55] Kaukolämpötilasto, District heating system 2023, Helen Mustikkamaa 12 GWh

[56] Näin lämpökuoppa varastoi syksyn energiaa talven varalle

The expansion of the Vaasa thermal storage facility is also based on new technology, namely raising the temperature level in the existing caves. This would enable significantly larger amounts of energy to be stored in the same space. If the project goes smoothly, this would greatly increase the cost-effectiveness of large thermal storage facilities. The Iso-Mustajärvi study[57] commissioned by Tampereen Energia estimated that the technology could even double the storage capacity. However, it is not clear that the technology is suitable for Tampere, for example. In pressurized thermal storage, the temperature would be around 140 degrees, which poses the risk of a steam explosion. The risk of a steam explosion is due to the fact that the hot and pressurized water will only remain in liquid form if pressure in the thermal storage is maintained. If pressure is suddenly lost, the water will instantly boil into steam and expand violently. This could cause an explosive pressure wave. This is a specific risk in a thermal storage facility located in a cave, because large amounts of water and energy are stored in a closed space.

A storage capacity of approximately 100 GWh is suitable for seasonal storage in a city the size of Tampere. A 90 GWh thermal storage facility is under construction in Vantaa, and its estimated cost in 2021 was EUR 75 million. However, in 2023, the estimated cost was EUR 100 million. According to the latest estimates, the investment in 2025 will be over EUR 200 million. This is a good example of how difficult it is to estimate the costs of new technologies. The amount of available waste heat varies by city, so profitability in one city does not necessarily mean good profitability elsewhere. In Hyvinkää and Vantaa, seasonal storage facilities can be very profitable because they generate a lot of waste heat as a by-product of waste incineration, relative to the size of the city.

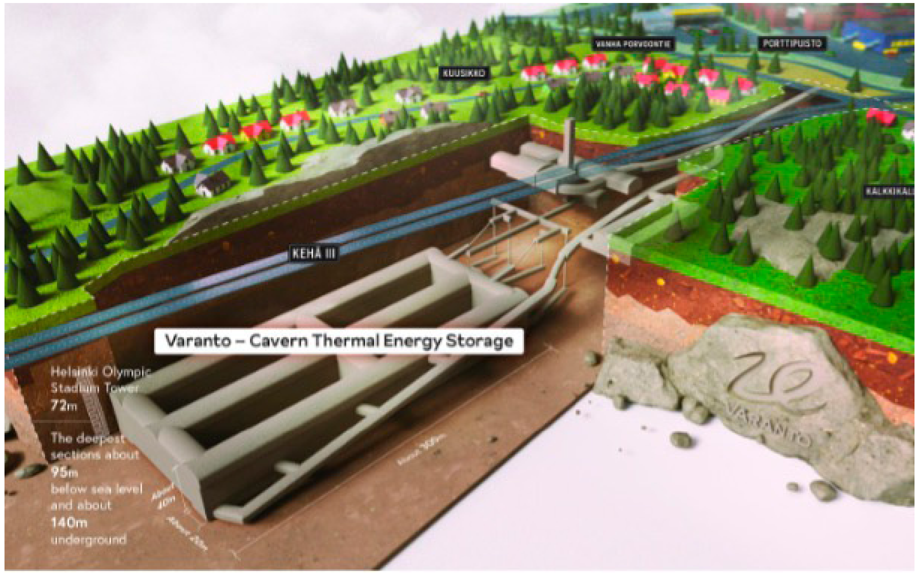


Figure 28. Vantaan Energia's Varanto thermal storage facility.[58]

In Tampere, 100 GWh would be enough to cover just under 5% of the heat demand for the entire year. Seasonal thermal storage systems are technically feasible and in a completely combustion-free system, they would be needed for heat production during low-wind cold spells. They have been chosen for all 2025 scenarios as a way to secure heat supply during cold moments.

Polar Night Energy from Tampere has developed a sand-based solution for heat storage. While the water temperature in traditional district heating thermal storage varies between approximately 45°C and 95°C, the temperature in the sand is 400°C. The sand is heated using electric heaters. In district heating production, this technology has advantages and disadvantages compared to water heating. The most significant advantage is the ability to provide heat at a high temperature without combustion. This makes the technology an attrac-

[57] Lämpöenergian varastointi Tampereen Energialla

[58] Varannon mediapankki - Vantaan Energia

tive alternative, for example, when used with heat pumps. Heat pumps do not produce enough hot water for district heating needs without the use of electric heating or a sufficiently high-temperature heat source. If electric heating and a sand battery are combined, the battery could be recharged replenish during the cheapest hours, and discharge heat to the heat pump as necessary.

There are three significant disadvantages. The first is that a sand-based battery can only be charged with electricity in the district heating network. Traditional district heating thermal storage can be charged using electricity, bioenergy or waste heat, thus enabling regulation of the district heating network and preventing the need to discharge excess heat into lakes. The second disadvantage is the price. If the sand battery is not used in an application where high temperature is beneficial, it is a more expensive option than building an electric boiler and traditional district heating thermal storage separately. The third disadvantage is the low discharge capacities. Based on ongoing projects, the sand battery operates with about ten times lower discharge power than, for example, water-filled steel thermal stores in relation to the storage capacity.

5.2 Electric boilers

- **Emission reduction potential = 2**
- **Cost-effectiveness = 4**
- **Availability = 4**

An electric boiler is basically a giant kettle. Electricity and cold water go in, and hot water comes out. Thanks to their simple technology, boilers can be fitted into a small space and they are inexpensive. They also go from zero to full power in minutes. Starting in the summer of 2022, the electricity tax for electric boilers in district heating networks has been almost eliminated, which has significantly improved their profitability. In Finland, they are currently being built at a rapid pace. In Tampere, our first 45 MW electric boiler was completed in Lielahti in spring 2023. Another two electric boilers will be commissioned in autumn 2025.

In the combustion-free scenario presented in this report, the electric boiler output power is 145–195 MW. Tampere's electricity consumption in extreme cold without electric boilers is approximately 400 MW. In principle, use of electric boilers therefore requires an almost 50% increase in capacity in the Tampereen Sähköverkko electrical distribution network. However, this is less of a problem than it sounds, because there is always a backup option for electric boilers if there is a threat of a shortage of electricity or electricity transmission.

The key to electrifying heating with electric boilers is flexible use. Increasingly, there will sometimes be too much electrical energy and sometimes there will be a shortage. In addition, the free transmission capacity in the electricity network varies depending on other demand and maintenance. It is not reasonable to plan electricity production and the electricity network so that electric boilers are assumed to operate around the clock regardless of the situation. Electric boilers are inexpensive, so they can be built alongside alternative power. An electric boiler can participate in almost all balancing markets, thus making it easier to balance the main grid. If the wind suddenly dies down, high price of balancing energy will lead to the boiler being shut down and alternative power being started up. This is much more cost- and climate-efficient than starting gas turbines to avoid a power shortage. Similarly, if there is suddenly an excess of renewable electricity available, electric boilers can be started quickly to alleviate the situation.

Proper regulation of electric boilers with transmission fees is essential. The price of electricity encourages electric boilers to be used during hours when cheap renewable electricity is available. However, the market price of electricity does not take into account bottlenecks in electricity transmission. On the other hand, an electric boiler does not burden the transmission bottleneck, if so agreed. The control signal must be strong enough. Balancing offers can be activated from the right geographical location to ease a bottleneck that occurs within the country. A good development target would be to have visibility into the adequacy of transmission capacity for more than an hour into the future.

City heating cannot be combustion-free if it relies on electric heating alone, because peak electricity production will still be based on combustion. Using electric boilers in extreme cold with no wind would also be expensive and irresponsible because the electricity system would already be under strain. Backup heat sources based on bioenergy or fossil fuels must be maintained alongside electric boilers. If fossil fuels are only used when electricity production also has to rely on fossil fuels, the climate impact is small, but a backup heat source would significantly improve the supply and security of supply compared to rigid dependence on electricity.

Electricity tax reduction

The transition to non-combustion-based district heating was accelerated by the electricity tax reduction that came into effect on 1 July 2022. As a result of the change, heat pumps, electric boilers and data centres with an output of over 0.5 MW will fall into a lower electricity tax bracket. This change significantly improved the profitability of electric boilers, and Finland has invested heavily in electric boiler capacity during the years 2022–2025.

The change in the electricity tax bracket required a national exemption from the EU. The Commission authorised the tax rate proposed by Finland for the period 1 January 2022–31 December 2027. To continue with a lower electricity tax rate for electric boilers after 2027, Finland will have to apply for an extension permit. If an extension permit is not applied for, the electricity tax bracket will move back to the higher tax category I. Taxation risks have also been increased by the EU's new Energy Taxation Directive, negotiations for which are still ongoing. It is not yet possible to say whether the Energy Taxation Directive will allow a lower electricity tax for low-emission heating solutions, like its predecessor, or not. For now, it is considered likely that it will.

In order to achieve the current climate goals, it is necessary to continue to secure a favourable electricity tax for heat pumps and electric boilers, either through a national extension permit or directly in the new Energy Tax Directive.

In Finland, it seems that tax decisions are now being made quite frequently as a result of the government's economic goals. The last budget session of the current government will be held in 2026, after which the parties will begin to publish their election programs for the next term. These will show how much political will there is to encourage low-emission and non-combustion-based heating solutions through taxation.

5.3 Waste heat

- **Emission reduction potential = 3**
- **Cost-effectiveness = 4**
- **Availability = 4**

Tampere has active in identifying various waste heat sources. After the first version of the study, it turned out that some of the previously identified waste heat sources will not be implemented in Tampere in the near future. On the other hand, new sources of waste heat have also appeared. The availability of waste heat depends on investments into suitable industrial activity in Tampere. This means that Tampereen Energia has only limited possibilities to build its combustion-free scenario based on waste heat.

If we wanted to increase waste heat production in the system, either significantly more heat sources that can be utilized must be found or the existing ones must be increased. Potential small-scale heat sources include ice rinks and refrigeration systems in shops. However, the size of these is so small that they are often be used to reduce the building's own heat needs. For example, at the Nokia Arena, cooling heat is recovered, which at best covers several tens of percent of the arena's own heat needs.

At the moment, it seems that the most promising sources of waste heat in Tampere will be waste heat from hydrogen production and data centres. Both of these offer significant waste heat capacities and heat recovery would improve the profitability of the projects. Other possible larger waste heat sources could include heat from the wastewater treatment plant and heat from biochar production.

The utilization of waste heat from the Sulkavuori central wastewater treatment plant has been thoroughly investigated. In many other cities, wastewater heat is already recovered. However, the conditions in such cities are more favourable than in Tampere. In Tampere, the wastewater treatment plant is in a bad location for use with the district heating network: it's on the wrong side of the bottlenecks and far from primary (water temperature-increasing) plants. If Tampere expands southward in the future and demand closer to the central wastewater treatment plant increases, the profitability of utilizing its heat will also increase.

Biochar production generates a significant amount of steady heat. A few years ago, it was still considered possible that biochar production would join the Tampere district heating network. In 2019–2022, biochar was produced in Tampere and an average of 0.5 MW of waste heat was supplied to the district heating network. It now appears that, at least in the short term, no biochar plants will come to Tampere, meaning that no waste heat will be available from them.

When planning waste heat recovery, it is necessary to take into account the unfortunate fact for the waste heat purchaser that if the production process ends or becomes more energy-efficient, the supply of waste heat will also end. In addition, the availability of waste heat is not constant throughout the year, but depends, for example, on the price of electricity and the weather, which poses risks to supply and security of supply.

Tampereen Energia is very interested in hearing about all new opportunities for utilizing waste heat.

Cogeneration of data and heat

Data centres are a constant source of waste heat available all year round, but there is currently a limited number of them in Finland. The location of data centres along the district heating network is essential for the recovery of waste heat. The location of data centres in remote areas means that valuable waste heat would remain unused. For example, Google's data centre in Hamina has not previously produced heat for the district heating network due to its suboptimal location for the network, but in the fall of 2025, the plan is to start recovering heat for the district heating network there too. A recovery plant of approximately 5 MW will be sufficient to cover 80% of the energy needs.[59] The total power of the data centre is approximately 200 MW, so a large part of the waste heat will remain unused in the future.

Construction work on Finland's largest data centre project began in 2024. This Microsoft project in Espoo will cover up to 40% of the district heating needs in the area. According to Fortum, this is the world's largest data centre waste heat recovery project and reportedly the largest single ICT investment in Finnish history. The project will see two data centres of equal capacity built in Espoo, one in Hepokorpi and the other in Kirkkonummi.

There is currently one data centre in Tampere which waste heat is available from. This is Nokia's Hatanpää Valtatie 30 data centre. The data centre's waste heat recovery began in spring 2022. Heat recovery capacity has increased significantly since then, and the plan is to increase it further in the coming years.

Since the spring of 2025, there has been a heated discussion about data centres, regarding issues like adequacy of electrical power, taxation, and security threats, since several projects have been announced. In Pirkanmaa, for example, a 30 MW data centre project is being prepared in Nokia's Kolmenkulma, which, if implemented, would be an investment of several hundred million euros.

In the spring of 2025, the government submitted a proposal to raise the electricity tax on data centres for public comment. However, the government has since submitted a new proposal for public comment, in which only the tax on electricity used in mining operations would be transferred from the lower electricity tax bracket to the general electricity tax bracket. At the same time,

[59] Googlen datakeskuksen lämpöä alkaa virrata Haminan kaukolämpöverkossa vuoden 2025 aikana

the Minister of Finance commented that another model for amending the electricity tax on data centres is also being prepared to take different types of data centres into account separately.[60] Ultimately, however, the government decided to move all data centres to a higher electricity tax bracket and is preparing to create a new support system for data centre investments if necessary. [61]

An increase in the electricity tax on data centres would weaken Tampereen Energia's opportunities to utilize waste heat in the production of district heating. The growing need for data centres is a global megatrend, so the tax reform mainly affects whether data centres can also heat Finnish cities at the same time. Locating data centres abroad means that Finnish low-emission electricity will not be utilized.

In addition to discussion about the appropriate tax levels, there has also been discussion about the adequacy of electricity transmission capacity for data centres. Fingrid issued statements on 30 January 2025 and 24 September 2025, in which it said that it would restrict new sites which consume over 10 MW in Uusimaa, Southwest Finland, Kanta-Häme and Pirkanmaa in 2025–2027, until major transmission line investments are completed. The transmission bottleneck has been caused by the end of Russian imports and the rapid shutdown of CHP production in Southern Finland, combined with a large number of connection agreements for electricity consuming projects and electricity storage that were concluded over a short period. Therefore, there should be enough electricity for data centres as long as the transmission lines are completed.

The hydrogen industry is starting slowly

In early 2023, the Finnish government announced a decision-in-principle to raise Finland to a leading position Europe's hydrogen economy. The goal is to achieve a 10 percent share of Europe's emission-free hydrogen production by 2030. This would mean an increase in annual hydrogen production to one million tons by 2030.

Fingrid's vision scenario for a "hydrogen mainstream" assumes that the electricity consumption of electrolyzers in Europe will be 1050 TWh in 2040. In this scenario, Finland's market share would be 10%, according to the target set in 2023, and industrial electricity consumption will increase more than fivefold by 2040, increasing to +158 TWh.[62] The waste heat from this would easily heat all the cities in the vicinity of which the factories would be located.

In early 2023, according to an estimate by the Finnish national broadcaster, Yle, there were up to 15 billion euros worth of hydrogen-related investments underway in Finland, totalling 26 projects. However, a large number of the projects are still in the planning phase, and some projects have announced that they will withdraw from the investments. For example, the renewable hydrogen production plant investment planned for Neste's Porvoo refinery was cancelled in 2024, even though the project received both investment support from the EU's Innovation Fund and energy support from the Ministry of Economic Affairs and Employment. The decision was justified by economic reasons and a decrease in demand due to changes in the distribution obligation legislation. Demand for renewable fuels has not grown as quickly as the first movers expected. Neste's decision reflects how challenging the market conditions are for hydrogen projects at the moment well.

The aim of a large number of the planned projects is to produce further refined products from pure hydrogen, not just hydrogen. However, Finland is also involved in the development of a hydrogen pipeline network of over 5,000 kilometres in the Baltic Sea region, so the goal is to transport large amounts of hydrogen as such to Northern Sweden, the Baltics and Central Europe.

The production of hydrogen and synthetic fuels has significant waste heat potential. For example, the Nordic Ren-Gas synthetic fuel production plant, which

[60] Datakeskusten ja kaivosten verotukea ehdotetaan poistettavaksi

[61] Datatalouden tiekartta ja datakeskusten verotuki

[62] Fingridin sähköjärjestelmävisio 2040: Suomi kohti kilpailukykyistä ja sähköistynyttä tulevaisuutta

is now making progress, will make significant amounts of waste heat available all year round to the Tampere district heating network. Nordic Ren-Gas Oy will produce synthetic methane from hydrogen for transport use at the plant. In the first phase, by 2028, an average of 20 MW of waste heat will be supplied to the district heating network, but as production capacity increases, it will be possible to obtain up to three times this amount of waste heat.

Hydrogen production, when combined with district heating networks, is energy efficient. The efficiency of hydrogen production is around 50%. If waste heat is recovered, the efficiency jumps to around 90 percent. Hydrogen production can be compared to the combined production of electricity and heat – the utilization of this heat is the reason that district heating networks were originally established. In CHP production, the main product is electricity and the waste heat is recovered for the district heating network. Perhaps in the future, hydrogen production will take on the role of electricity production by providing energy-efficient waste heat to customers of district heating networks. Hydrogen production has been modelled in a significant number of scenarios presented in the study.

5.4 Hydrogen and synthetic fuels

- **Emission reduction potential = 2**
- **Cost-effectiveness = 1**
- **Availability = 2**

For the sake of clarity, this chapter is about the combustion of hydrogen for heat, not waste heat from hydrogen production. Hydrogen will play a rapidly growing role as Europe seeks to phase out Russian natural gas. The first hydrogen-producing plant is expected to start up in Tampere by 2028. Nordic Ren-Gas Oy will produce synthetic methane from hydrogen for transport use in its plant. Tampereen Energia is happy to use the waste heat generated in the process to heat the city.

The European energy system relies much more on gas infrastructure than Finland. Achieving carbon neutrality in the European energy system will require huge amounts of hydrogen. The scale is comparable to the current fossil fuel industry. In 2021, the EU used about 4 100 TWh of natural gas. Natural gas will not be replaced on a one-to-one basis by hydrogen, but rather as much as possible directly by electricity and by increasing energy efficiency. As stated in Chapter 5.3, replacing even a small portion of this with hydrogen produced in Finland could multiply Finland's electricity consumption.

The energy crisis has highlighted that electricity in Finland is cheaper and cleaner than in the rest of Europe. In addition, EU regulations are directing the production of hydrogen specifically in line with wind power production. On the global market, renewable hydrogen competes with cheaper hydrogen made from natural gas, and is not competitive if carbon dioxide emissions are not paid for. Regulation is therefore the most significant force shaping the sector in the early stages of the hydrogen industry.

Hydrogen technology offers two ways to provide heating: the utilization of waste heat generated in hydrogen production and the use of hydrogen directly for heat. Hydrogen burns with oxygen to form pure water, so it is completely carbon neutral, assuming that hydrogen production has been carbon neutral. The emission reduction potential, cost-effectiveness and availability presented at the beginning of this chapter refer to burning hydrogen for heat.

For the time being, it is not worth burning hydrogen for heat. Hydrogen will be in short supply and its production is quite expensive. On the other hand, transporting and storing hydrogen is challenging. It is not at all impossible that in a hydrogen plant built mainly for other needs, using hydrogen on the same plot in a CHP process at a time of high electricity prices will prove profitable. However, more resource-efficient carbon-neutral investment options are available, mainly in the energy industry. The best uses for carbon-neutral hydrogen are likely to be found in industry and heavy transport, where emission reductions are otherwise difficult to implement. So far, we have not modelled the burning of hydrogen for energy in our scenarios.

5.5 Heat pumps

- **Emission reduction potential = 2**
- **Cost-effectiveness = 3**
- **Availability = 4**

Heat pump technologies can be divided into different categories depending on the heat source used. Heat pumps used in apartments and small sized buildings are either ground-source, air-to-water (ATW) or exhaust air heat pumps (EAHP). Air-to-air heat pumps are also common, especially in detached houses and cottages. In district heating production, industrial-sized heat pumps can utilize centralized waste heat sources, such as wastewater and industrial processes.

Air-to-water heat pumps

In air-to-water heat pumps, heat is transferred from the outdoor air to a water-circulating heating system. The advantage of an air-to-water heat pump is that it can be built on a large scale without a separate heat source. The placement of the heat pump requires some planning, as the units emit noise and cold air, which can negatively affect other uses in the area.

A few plants have been built in Finland, especially in conditions where they can produce both heating and cooling. For example, in the summer of 2023, Fortum's 11 MW plant in Vermo started up, and in 2025, Helen's 14 MW plant in Salmisaari started up. Both produce both heating and cooling. Both received investment support. The Salmisaari plant cost around EUR 13.5 million, meaning the cost is around EUR 1 million/MW.

A system based on an air-to-water heat pump is visualized below. The problem with the technology is that availability is inversely proportional to demand. The farther the outside air is below freezing, the more difficult it is to extract heat from the air, and on the other hand, the greater the need for heat in the city. This problem has been illustrated by the zero output of the heat pump during frost peaks. Tampere has not invested in air-to-water heat pumps, since there is no shortage of fossil-free heat in the warmer months of the year, and in winter, it would be cheaper to invest in an electric boiler with similar operating costs. Air-to-water heat pumps are a good option if additional heat production based on heat pumps is needed during the warm and cool seasons.

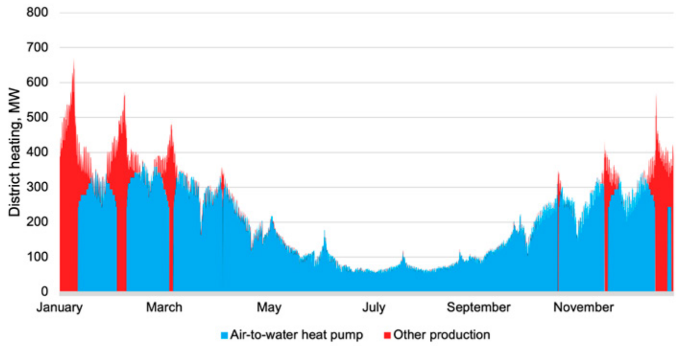


Figure 29. A heating system based on an air-to-water heat pump needs a second heating system in parallel for cold days.

ATW production has been added to the completely combustion-free scenario presented in the study (Waste and Surplus scenario). If no other heat sources are available, ATW is a more energy-efficient alternative than an electric boiler in continuous production. Adding ATW to the scenarios increased the investment cost considerably, because it did not reduce the number of electric boilers needed. The heating system must be dimensioned for the most severe frosts, so heat production methods that do not produce heat at that time are problematic.

Lake heat

A heat pump that uses Lake Näsijärvi as a heat source has been proposed in Tampere, for example, as an alternative to heating Hiedanranta. A seawater heat pump has also been studied for heating in Helsinki. For example, such a seawater heat pump already exists in Stockholm, but the shape of the seabed and the ocean currents there make the technology profitable. In the case of Helsinki, the shallow seawater would make it significantly more expensive to implement than Stockholm. In fact, the project in Helsinki was quietly abandoned. In Tampere, these problems would be even greater.

The energy company Helen has studied the suitability of seawater as a heat source for heat pumps. The company's report states that in practice, water at 3 degrees is needed to ensure the operation of a heat pump, and the probability of water this warm in winter at a depth of 35 meters is less than 10–25%.[63] If we assume that the bottom of Lake Näsijärvi is as cold as the seabed off Helsinki, the result is that the lake water is not suitable as a heat source for a heat pump to producing heat in winter. There are only a few places in Lake Näsijärvi where the depth is over 35 meters, and even in these places there are significant uncertainties regarding the ability to obtain continuous heat output.

Heat pumps – hybrid district heating

Hybrid district heating means that a heat pump is added to the building in addition to district heating. The pump can be a ground-source heat pump, EAHP or ATW, which only produces some of the building's heating needs. The rest of the heating needs are supplied by the district heating network. Reliable district heating also guarantees the availability of heat if the heat pump fails.

Weijo studied heat pump-district heating hybrids in her thesis.[64] It was difficult to find a typical hybrid system. EAHP was the most common type in numbers, but these were also very different from each other. The average impact on the district heating need is illustrated in Figure 30.

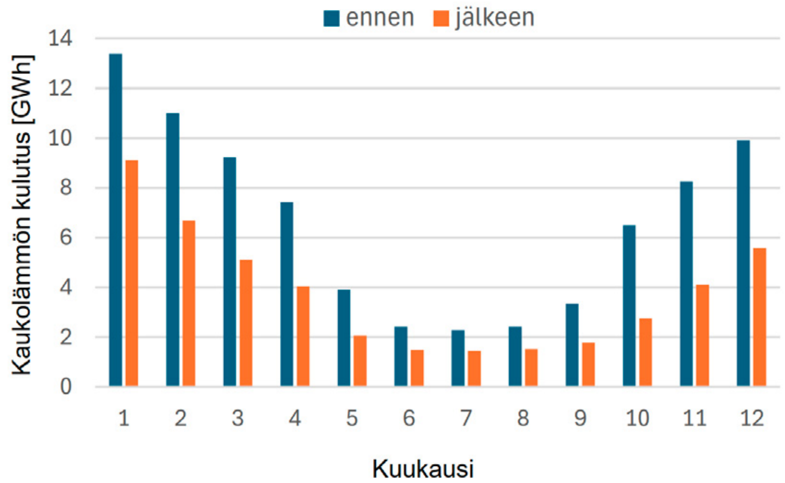


Figure 30. District heating demand before and after EAHP installation by month. Legend left to right: before, after.

In district heating hybrids, profitability is sought on a building-by-building basis through savings in heating costs, but at the same time the electricity consumption in the properties increase. The study also found properties where heat pumps clearly do not work as planned. This also supports the findings and conclusion of a study[65] commissioned by the Kiinteistö Liito, the Finnish Real Estate Association. Only about half of the housing companies in the study said they had used an external energy or building services expert to carry out project planning. In addition, as many as one in three said that no project planning was carried out at all. According to Petri Pylsy of the Finnish Real Estate Association,[66] utilizing an impartial expert is an essential part of a successful ground-source project. The study also found that about half of the respondents said that the operation of the heat pumps is not monitored in any way. The poorly functioning hybrid solutions found in Weijo's study confirm that a housing company which purchases heat pumps must also monitor the operation of

[63] Merivesilämpöpumput kiinnostava mahdollisuus myös Helsingissä

[64] Henriikka Weijo, Kaukolämpöasiakkaiden hybridiratkaisut, diplomityö, Tampereen yliopisto, Ympäristö- ja energiatekniikan tutkinto-ohjelma, 2025.

[65] Uusiutuvat energialähteet asuntoyhtiöissä

[66] Puolueeton hankesuunnittelu avainasemassa taloyhtiöiden lämmitysremonteissa

their equipment. Savings on the design, implementation and monitoring of the equipment can turn out to be very expensive.

Hybrids are typically designed to produce the temperature required by the building, which is lower than the temperature of the district heating network. If this is the case, the hybrid cannot be bidirectional, meaning it cannot feed energy back into the district heating network. Water that is too cold would disrupt the heat supply of the neighbours. In any event, the building would have excess energy mainly in the summer. The problem with the heating system is not heating in the summer, so the benefit of bidirectionality would actually not be very great.

Low-temperature district heating network

Tampereen Energia's goal is to build an advanced heating system in Hiedanranta, based on a new type of low-temperature district heating network. The water circulating in the network is around 70 degrees, while the water circulating in the district heating network is normally 80–120°C, depending on the air temperature. Like regular district heating, the solution is bidirectional, meaning the customer can both buy heat from the network and sell heat to the network. The lower-than-normal temperature makes it easier to connect waste heat and heat pumps to the network in the Hiedanranta area. The district heating system is part of Hiedanranta's energy ecosystem based on a circular economy, which also includes non-combustion-based heat production.

Flue gas scrubbers

The efficiency of power plants can be improved with flue gas scrubbers and heat pumps. In a power plant that does not have flue gas scrubbers, flue gases must be discharged into the chimney at temperatures above 100 degrees. Flue gases contain substances that corrode the flue stack if water vapor condenses in the flue. The flue gas must therefore be hot enough that the water remains in vapour form. This causes a large loss of heat, because a large amount of energy is bound up in the water vapor.

A flue gas scrubber enables the recovery of this heat. In a flue gas scrubber, the flue gases are cooled to the district heating return temperature (approximately 45–55°C), at which point the water condenses and most of the waste heat is recovered. The flue gases exit the flue stack at approximately +50 degrees. This waste heat is not warm enough to be used directly for district heating, but it is an excellent heat source for heat pumps. In Tampere, flue gas scrubbers are in use at the Naistenlahti 3 power plant, the Tammervoima utility power plant and the Hervanta wood chip heat plant.

When a heat pump is installed after the scrubber, the flue gases can be cooled down to as low as 10 degrees and the remaining moisture in the flue gas can be recovered. Such a heat pump can operate with a high COP, depending on the amount of heat recovered, in the range of 3 to 5. The electricity for the heat pump is obtained directly from the power plant, so the combination is a very efficient way of producing heat. However, the overall system, which includes the power plant, is not actually combustion-free, since the heat produced by the heat pump is not waste heat according to the strict definition (Commission Communication C/2025/2238), because one of the main products of the process is already heat.[67] Currently, without heat recovery, the heat would be lost up the flue, so according to more commonplace definitions, and the statistical methods of Energiateollisuus Ry, the Finnish Energy industry organisation, this kind of investment could be viewed as combustion-free waste heat. A heat pump loke this was brought into operation at the Naistenlahti 3 power plant in 2025.

5.6 Geothermal heating

- **Emission reduction potential = 3**
- **Cost-effectiveness = 2**
- **Availability = 1**

[67] EUR-Lex - 52025XC02238 - EN - EUR-Lex

The principle of geothermal heat is simple. A hole is drilled into the rock through which cold water is circulated. The water heats up and the rock cools down. At the surface, the heat is recovered and the water is returned to circulation.

The cost-effectiveness of geothermal heating depends a lot on how volcanic the area is, or more precisely, how quickly the rock heats up as you drill downwards. Finland is one of the least volcanic areas in the world, so the rock heats up very slowly. This means that the hole you drill must be very deep. In a volcanic area, such as Iceland, it is sufficient to drill a shallow hole and the hole will produce scalding steam. In Finland, we have to drill deep into hard bedrock to get even lukewarm water. In theory, the ground-based heat could heat the whole of Finland. In practice, it could probably be done much more cost-effectively and with just as few emissions in another way.

There are two basic types of geothermal heat used for district heating: deep and medium-deep geothermal heat. With deep geothermal energy, a borehole is drilled deep enough to obtain water at a temperature of about 100 degrees Celsius. In theory, this is suitable for direct district heating. There are many practical challenges with the cold rock of Finland, including water cooling on the way back up. Using medium-deep geothermal energy reduces drilling costs and boreholes are only drilled as deep as is easy to reach. However, in this case, only lukewarm water is obtained from the borehole. The lukewarm water must be heated until it is hot using a heat pump and the cold water then returned to circulation. With medium-deep geothermal energy, you save drilling costs, but you have to pay for the heat pump and the electricity used by the pump.

In the spring of 2022, a deep geothermal energy pilot project was concluded in Lake Tarastenjärvi in Tampere. In this joint project, which involved fourteen other Finnish city energy companies, the aim was to drill a geothermal well about three kilometres deep and gain experience in using water-powered DTH drilling technology and to learn about the potential of geothermal energy in Finnish soil.

The depth of the well was 2 230 meters. The mine has an estimated continuous output of 0.5 MW. The drilling cost was EUR 1.5 million. The temperature of the water pumped up is a little over 20 degrees, so it requires a heat pump and priming (auxiliary heating) to be a heat source.

The most significant uncertainties with geothermal energy come from the drilling costs. With medium-depth geothermal energy, the costs and temperature levels are quite well known, and they do not seem to be favourable compared to other alternatives. With deep geothermal energy, there are more unknown variables. Based on current information, it seems unlikely that deep geothermal energy would be cheaper in Finland than other forms of heating.

5.7 Small nuclear reactors

- **Emission reduction potential = 4**
- **Cost-effectiveness = 3**
- **Availability = 2**

Nuclear power can provide combustion-free and carbon-neutral heat, and as much as is needed can also be built into a compact space. Its emission reduction potential is therefore large and the development of nuclear district heating is ongoing. Projects do take a lot of time, but there have been many concrete development steps in the last two years, and support for nuclear power has continued to be high.

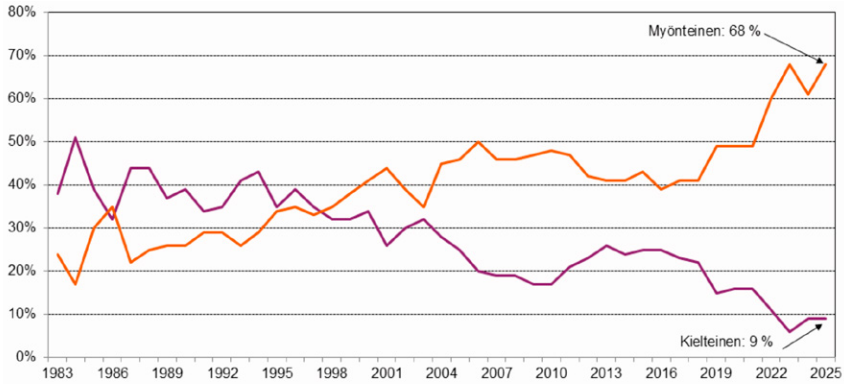


Figure 31. The development of support for nuclear power 1983–2025, general attitudes towards nuclear power as an energy source. [68] *Positive sentiment is 68% and negative is 9% in the most recent poll.*

SMR (Small Modular Reactor) is a broad term that refers to a wide variety of nuclear reactors. Their reactor capacities can range from tens to over a thousand megawatts. Some SMR models are designed solely for heat production for district heating networks, some produce both heat and electricity, but most are traditional condensing power plants. These differences make using the SMR term difficult: it does not indicate the actual size, characteristics, or whether the primary form of production is electricity or heat. For this reason, we try to avoid using the term SMR in general and also in this report.

There are several reactor concepts available around the world, the most advanced of which are NuScale (USA), GE-Hitachi (USA-Japan) and Rolls-Royce (UK). However, these "small" modular reactors are too large for Finnish district heating networks and are designed with electricity production in mind. The smallest of them is 280 MWe (four-module NuScale), Ge-Hitachi's BWRX-300 is 300 MWe and Rolls-Royce's UK SMR is 470 MWe. The MWe designation stands for megawatts of electricity production. Roughly speaking, when a plant produces one megawatt of electricity, it also produces two megawatts of heat.

For example, a BWRX-300 would produce about 600 MW of district heating in addition to electricity.

The Tampere district heating network is the second largest district heating network in Finland, after Helsinki, and about the same size as Fortum's Espoo network. The appropriate size of reactor for Tampere would be in the 50–100 Mwe class, making about 100–200 MW of heat. Even the smallest of the reactor concepts is therefore about three times too large. Finland could accommodate at most one reactor project of this scale, to produce both electricity and heat for the capital region.

There are also concepts of a smaller size. Steady Energy is developing a 50 MWth reactor and Calogena a 30 MWth reactor that produce only heat. These reactors are about one hundredth the size of Olkiluoto 3. Both utilize as much traditional technology as possible, for example, technology already proven in nuclear powered icebreakers. Very few nuclear power plants have been built in Europe in recent decades and never for district heating in Finland, so getting the appropriate licenses will be a significant risk for the first plant. In subsequent projects, choosing proven technology would minimize technological risk and make licensing easier. A reactor that produces only heat makes it easier to design plants that also produce electricity safely, thanks to the lower temperature and pressure levels.

Many different estimates have been made about the costs of nuclear district heating, but they are reasonable compared to other alternatives with the same potential. In practice, however, no projects have been built, so the cost-effectiveness is based entirely on estimates. With electricity generation projects, the price has often multiplied during the development phase. With nuclear district heating projects, we can give reasonable explanations for why this would not happen – there are fewer components, the systems are simpler, and since the plants are based on proven technology, the uncertainty in the cost estimates is lower. In any case, the profitability estimate describes our understanding of what the cost level would be if projects progress favourably from

[68] Ydinvoiman suosio huippulukemissa - Energiateollisuus

the perspective of nuclear district heating suppliers. This cost level is therefore not a forecast, but a prerequisite if nuclear district heating is to play a significant role in Finland.

The cities of Helsinki and Kuopio are furthest along the path of acquiring nuclear district heating in Finland. Helen's goal is to have nuclear district heating in Helsinki in the early 2030s.[69] Kuopion Energia is preparing to replace its Haapaniemi power plant in 2035. Small nuclear power plants are one of the options being actively studied, and an EIA procedure is currently underway.[70] Thanks to this rapid development, we have raised our assessment of the maturity of the technology since the previous report.

In the autumn of 2022, four councillors from different parties drafted an initiative in Tampere to investigate the location of a nuclear power plant in Tampere. As a result of the initiative, the Master Planning Unit drafted a report about it. A nuclear district heating plant must be located near places that are difficult to evacuate or critical to the functioning of society, although "near" means different things for the Olkiluoto 3 power plant and a small heating plant. Dense residential areas should be avoided, for reasons of general acceptability. However, heat cannot be transported very long distances. A somewhat remote area that is already in industrial use would probably be the most viable location. The study made a very preliminary assessment of the suitability of the Kolmenkulma, Hankio, Naistenlahti and Rusko areas as potential investment locations. None of these would be problem-free, so further studies are needed.

Getting nuclear district heating from the planning table to reality requires the joint efforts of many parties. Political approval, a regulatory framework, licenses, technology, a supply chain, a commercial need for the end product, capital for risk investment and a company willing to take a business risk are all needed. An organization is also needed that can safely and cost-effectively operate the plant. In principle, all parties would like to avoid unnecessary work, and for the other factors to be in place before investing their own resources. The role of the state is therefore central in the development of nuclear district heating. If social approval is found, the state can offer feasible regulation and reduce financial risks for participants.

Constructing and operating nuclear district heating is a bad fit for the business of district heating operators. To ensure power plants are safe, nuclear energy experts must design, license and build them. Specialized high-level expertise is also required to operated, maintain and manage nuclear district heating plants. And, to ensure safety and continuous development, one precondition is that the organisation responsible for maintenance must have the right to shut down the plant to carry out maintenance when necessary. The organizational structures must be carefully considered so that responsibility for the safety of the plant is unambiguous, and so that the responsible party has the necessary competences to ensure safety in practice.

The EcoSMR project proposed that at least three small nuclear power plants would be needed to enable providing maintenance and operator services as a service to be a profitable business. This also highlights the need for a national small nuclear power strategy. Operations need to be scaled to a sufficiently large level that market-based operations begin to pay off in all parts of the supply chain. With energy investments, the statement that production is profitable but that it also needs subsidised may sound paradoxical, but it can also be true. Getting an entire energy production supply chain up and running in is enormously expensive. With new energy technologies, starting operations has always required public investment, after which market forces can maintain profitable operations. The first implementations will require subsidies, after which operations are profitable on market terms. This is what happened with wind power.

In Tampere, the next step towards nuclear power would be a more detailed mapping of locations. After this, an EIA and plans could be drawn up. If this is done, drawing up and approving the plan, including objections, would take an

[69] Helen etenee kohti polttamattomuutta käynnistämällä ydinenergiaohjelman

[70] kuopionenergia.fi/vastuullisuus/pienydinvoima

estimated five years. This would also be a significant investment. For example, Fennovoima's EIA report is 425 pages long. Such an extensive study is not needed for a nuclear district heating plant, but the cost would still be hundreds of thousands of euros.

5.8 Solar heating

- **Emission reduction potential = 1**
- **Cost-effectiveness = 1**
- **Availability = 4**

Technically, there is no problem in adding solar heat production to the system, even hundreds of megawatts, as long as the output is balanced with sufficiently large thermal storage. The problem comes from the inverse availability of production in relation to demand. Heating in the summer is easy, while seasonal storage is expensive and loses a significant part of the stored heat during the year.

Land along the district heating network is valuable, so for solar thermal fields, either an additional network would be needed separately or solutions more expensive than field installations would be required. With rooftop installations, on the other hand, solar heat competes with photovoltaic panels that produce solar electricity. The current trend seems to be that rooftops are more likely to be occupied by photovoltaic panels. Large-scale solar heat does not bring anything to the system that could not be provided by some other form of production with equally low emissions, but more cost-effectively. This was examined in more detail in previous versions of the report.

5.9 Carbon dioxide capture

- **Emission reduction potential = 4**
- **Cost-effectiveness = 2**
- **Availability = 2**

Carbon dioxide capture is not itself a form of heat production, but the metrics presented here describe the capture and utilization or storage of carbon dioxide associated with bioenergy (BECCUS).

In capture, carbon dioxide is separated from the flue gas generated by the combustion processes in a power plant. Absorption is the most mature of the separation technologies. In this, carbon dioxide is separated from the flue gas stream by dissolving it in an absorbent, after which the carbon dioxide is released as a clean gas stream in the second part of the process. At the same time, the absorbent is regenerated and can be recycled back to the beginning of the process. Absorption consumes heat and electricity.

After carbon dioxide capture, it can be utilized as a raw material or stored. Carbon dioxide is utilized, for example, in the production of synthetic methane and methanol or in biopolyester products. Carbon dioxide can also be refined into solid carbon products, such as carbon nanotubes and carbon fibres, using molten salt electrolysis. These carbon products can be utilized, for example, in the battery industry and concrete production.

From a technical perspective, there are no insurmountable obstacles to carbon dioxide capture. The most significant barriers to implementation come from the lack of economic incentives and lack of carbon dioxide transport infrastructure. There are no geological formations suitable for carbon dioxide storage in Finland, so carbon dioxide must be transported to old oil and natural gas deposits in Norway or Denmark, for example, or used in products.

An alternative to geological storage of carbon dioxide is the storage of carbon dioxide in minerals. A mineral suitable for this purpose is, for example, serpentine, which theoretically has a carbon dioxide storage potential of up to 20–30 Mt per year in Finnish soil. In theory, carbon dioxide can also be stored in mining waste, such as magnesium and calcium silicates, but accessing these in Finland is challenging. The technological maturity of carbon dioxide mineralization is not as high as that of geological storage of carbon dioxide.

Tampereen Energia sees potential in carbon capture and is ready to move forward as soon as it is economically and politically feasible. During 2022–2025, Tampereen Energia carried out several studies regarding the technical implementation of carbon capture for both the Tammervoima utility power plant and the Naistenlahti biopower plant. More information on carbon capture is provided in section 4.3.

5.10 Other forms of heat production

On the road towards a combustion-free and carbon-negative system, it is also necessary to examine the following two technologies, which will probably play some role in the future heating system. This chapter does not give these forms of production a score like the technologies presented earlier, as these technologies are not combustion-free or carbon-negative. However, reviewing them essential for understanding the overall national energy system.

5.10.1 Waste incineration

In Finland, more than half of municipal waste is incinerated, because energy recovery is mandatory due to the ban on landfilling organic waste. Economic control measures targeting waste incineration plants will not effectively increase the recycling rate, but resources must be allocated to facilitate household sorting and transfer waste incineration emissions to a sector where control can be targeted at the right point to produce real emission reductions.

In the early 2000s, use of landfill for final disposal of waste was first reduced by increasing the landfill tax, and then a landfill ban on organic municipal waste came into force in 2016. Several waste incineration plants started up in Finland around 2010, and around 2017 the proportion of waste used for energy recovery stabilized at around 60% of the total amount of municipal waste.

Waste other than municipal waste is also utilized in energy production. Other combustible waste includes, for example, some of the organic waste streams from industry and construction. Of the power plants classified as waste incineration plants, approximately 75% of the capacity is reserved for municipal waste and the rest for industrial waste streams.

Since municipal waste provides the majority of Finnish waste incineration capacity, and there is the potential to implement the waste hierarchy more effectively than at present, this chapter focuses on examining the energy recovery of municipal waste.

The generation of municipal waste is cyclical; it decreases in recessions and increases in booms. The amount of municipal waste primarily follows the purchasing power of households, and waste generated in both housing and services is classified as municipal waste. A study by LUT University has found that a typical 1% increase in GDP increases waste by an average of 0.4–0.5%.[71]

In 2023, the amount of municipal waste decreased from the previous year (Figure 32), but waste generation per person is still higher than the EU average. The decrease in the amount of municipal waste from 2022 onwards has been influenced by the refinement of waste data statistical methods. The EU's reporting rules and the national waste information system were revised in 2022, which changed the definition of waste streams classified as municipal waste. This accounting change explains most of the sudden drop seen in the statistics. At the same time, it complicates comparisons with previous years. Changes in the statistical method and economic fluctuations caused by various crises in 2020–2023 obscure the assessment of long-term trends.

[71] Sustainability of Waste Management System: Waste Generation and Collection

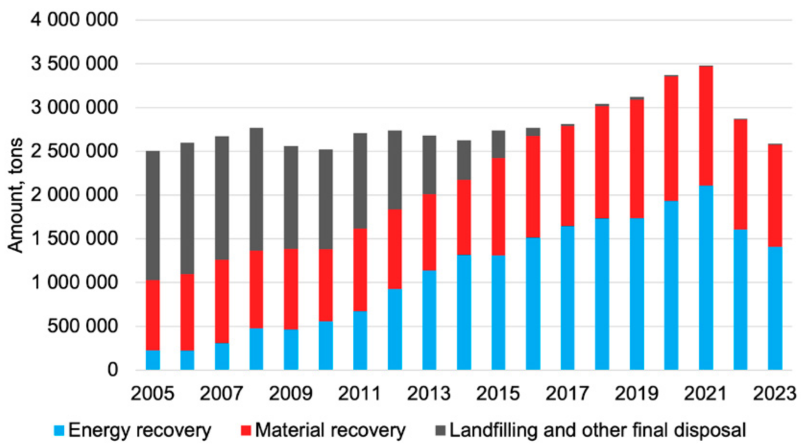


Figure 32. Amount of municipal waste by handling method.[72 73]

Finland also currently processes waste imported from abroad. In 2023, imported waste accounted for approximately 7% of all waste recovered for energy.[74] This is due to the relatively high waste incineration capacity of the Nordic countries compared to the rest of Europe, where a significant amount of municipal waste is still sent to landfills. Finland's role in European waste processing will depend on the development of recycling rates in other countries and on how waste incineration capacity develops in the EU. No imported waste has been incinerated in Tampere, and the energy recovery of imported waste has been concentrated closer to coastal terminals.

The recycling rate of municipal waste in Finland has remained fairly stable over the past decade, at around 40%. Like other EU countries, Finland has committed to recycling 60% of municipal waste by 2030 and 65% by 2035. In 2023, more municipal waste was recycled than before, approximately 44.6%.[75]

The emissions from energy recovery from municipal waste in Tampere are as follows. The top curve reflects emissions according to the current plan, which assumes that both the waste sourcing area and composition remain almost constant. The middle curve shows the situation if national recycling targets are achieved so that recycling of biowaste in particular becomes more common (forecast 1). The lowest curve shows the situation if municipal waste recycling targets are achieved while the composition of the waste remains constant (forecast 2), i.e. plastic recycling will follow biowaste recycling and become significantly more common. It is assumed that fossil emissions from energy recovery from waste in Tampere will remain at about 60–80 ktCO_2 per year. For comparison, Tampereen Energia's total emissions forecast for 2027 is 144 ktCO_2 (market-based scope 1 emissions).

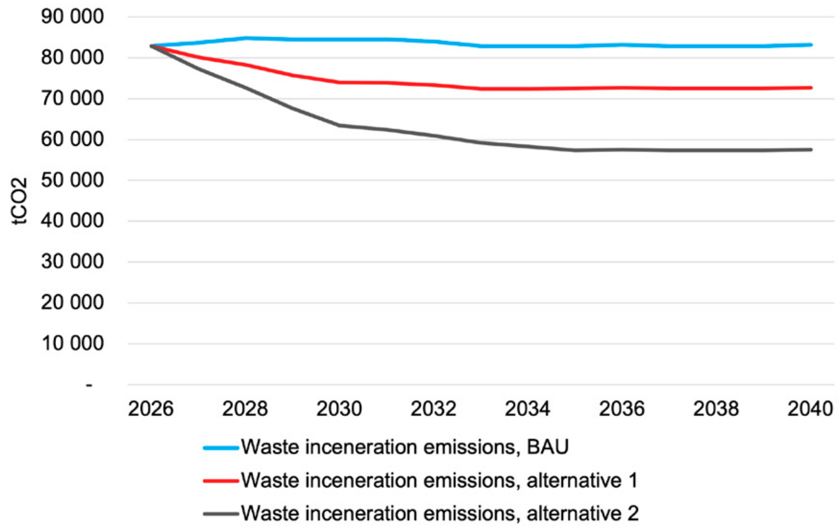


Figure 33. A forecast of Tammervoima's fossil fuel emissions.

[72] Yhdyskuntajätteet käsittelytavoittain vuosina, 2002-2023

[73] Yhdyskuntajätteet

[74] Jätteiden tuonti Suomeen kasvoi vuonna 2023

[75] Yhdyskuntajätteiden määrä väheni vuonna 2023

If the recycling target for 2030 is achieved, assuming that the total amount of waste generated remains constant, approximately 40% of municipal waste will be diverted to energy recovery. This means that the current capacity (60% of the waste stream) will be partially underutilized. If the amount of municipal waste diverted to energy recovery in Finland decreases, production volumes will also decrease. However, we do not expect that the Tampere plant will be the first waste incineration plant to be shut down in Finland due to its central location and its advanced carbon dioxide capture project.

Of course, if waste incineration is profitable, waste could also be imported for incineration from elsewhere in Europe. However, this would most likely happen in coastal areas, and could be prevented by separate regulation if necessary.

Waste-to-energy management instruments

The expansion of the EU emissions trading system to include waste incineration in 2028 is a significant steering mechanism that will have direct economic impacts on waste management. Now that waste is included in the emissions trading system, waste incineration plants will have to buy emission allowances for fossil-based components that are present in the waste stream.

There was already discussion about taxing waste incineration nationally before the emissions trading system included it. The EU emissions trading system is a market-based steering instrument, compared to which a national waste tax would be inflexible. A study by the Ministry of the Environment concluded that a national tax would be an ineffective, overlapping form of guidance. The impact of the tax on the recycling rate would be marginal, because the biggest challenge is in implementing sorting, not in the lack of a price signal.[76]

To avoid double counting, Finland's policy is that emissions from waste-to-energy management are calculated in the energy sector, not in the waste management sector. The background to this is the IPCC Guidelines for National Greenhouse Gas Inventories, which outlined this in the past.[77] Calculating emissions in the energy sector obscures the mechanism by which emissions are generated. Utilizing non-recyclable municipal waste as energy is a mandatory measure, as landfilling must be avoided. Taking emissions into account as a part of district heating production will now guide the choice of heating method, but will not affect actual emissions. Even if district heating consumption decreases, waste will still need to be handled.

5.10.2 Biogas and biooil

Using biogas and biooil for energy production is technically easy, as they can typically be used in the same plants that use fossil fuels. The use of biooil may require some additional investments in existing plants, depending on the quality of the oil. However, bio-based alternatives are not combustion-free and often not carbon-neutral technologies. They are nevertheless important renewable energy-based means of managing the power of the heating system.

Usually, the price of biogas and biooil is clearly higher than fossil natural gas due to the more expensive raw material sources, decentralized small-scale production and a more expensive refining and distribution process. Renewable fuels have environmental benefits and their production increases the energy self-sufficiency of the European region. For example, the REPowerEU programme aims to increase European biogas production to an annual level of up to 350 TWh by 2030, which would mean a significant proportion – around 15% – of the region's total gas consumption. The development of the biogas sector is promoted by various public support mechanisms, such as feed-in tariffs, distribution obligations, and tax and investment subsidies.

As part of the free internal market, both domestic biogas and biogas distributed through the common European gas network are used in Finland. In emissions trading, biogas is defined as emission-free because it meets the criteria of the EU's Monitoring and Reporting Regulation and the Renewable Energy Di-

[76] Selvityksessä etsittiin keinoja edistää jätteenpolton kiertotalous- ja ilmastotavoitteita

[77] Incineration and open burning of waste

rective. A batch of biogas can only be consumed once. This purchase accounting and content-related monitoring is implemented by means of a Guarantee of Origin granted to biogas and the associated sustainability certificates. The system is Europe-wide and is based on the Renewable Energy Directive and local legislation. In other words, biogas can be used across Europe, as long as the gas supply point and the consumption destination are within the same gas network.

Biomethane has numerous overlapping markets, for example the transport distribution obligation market, the market linked to emissions trading, the feed-in tariffs for electricity production, the gas heating market and various voluntary compensation-based solutions. When these are combined with local legislation, support mechanisms and varying sustainability certificates, the result is a patchwork of solutions, the transparency of which is sometimes very poor.

Biogas and biooil have been excluded from the modelling of this report, as it does not seem sensible to install carbon dioxide capture equipment in plants that use them as fuel, and they therefore do not contribute to carbon negativity. If necessary, they can be introduced with relatively small investments and on a quick schedule to secure the supply of heat for peak consumption with low emissions. In Tampere, both biogas and biooil have been used from time to time to replace fossil fuels, depending on availability.

5.11 Energy production and consumption in buildings

The Energy Efficiency First principle means that in all energy-related decisions and investments, the aim must be to first reduce energy consumption and improve energy efficiency before investing in new energy production. The aim is to ensure that the energy used is used as wisely and sustainably as possible. When designing buildings, builders have an incentive to build slightly less energy-efficient buildings at a lower price, because it is very difficult for the buyer of a new building to assess the energy efficiency of the building superficially, and it is much easier to assess the price. This is why the energy efficiency of construction is regulated. In principle, this is should be supported, but tightened and complex regulations have resulted in some unwanted side effects.

E-value and energy consumption in buildings

Energy efficiency is measured in accordance with EU regulations in terms of the E-value. An energy certificate, in which the E-value is central, is intended to provide information about the energy efficiency of a building, especially for sales and rental, and is also required during the permit phase for new buildings. The E-value regulates the minimum level of energy efficiency that new buildings must achieve. Therefore, the details of the calculation method affect the competitive situation in the heating market. The largest sources of distortion are:

1. The E-value measures purchased energy and the calculation boundary is an individual building. If a heat pump is inside a property, it is treated differently than if the same heat pump were, for example, in a district heating network.

2. The coefficients for the forms of energy are national and the same coefficient is used for each point in time. The calculation does not take into account whether the building uses waste electricity or electricity produced with fossil fuels. The calculation also does not take into account the characteristics of local district heating.

The current coefficients, 1.2 for electricity and 0.5 for district heating (ratio 2.4), favour heat pumps in buildings, which have a COP value of around 3.5 in Tampere's energy certificates. This gives heat pumps a significant advantage in these calculations. As long as the E-value is used to compare, for example, ground-source heated buildings with each other and district heated buildings with each other, this is not a problem. Today, this construction regulation guides the choice of heating methods among competing low-emission technologies. It is therefore beginning to guide energy policy without having a concrete link to climate impact. See more on this in Chapter 7.

Although the E-value does not take into account the actual energy consumption of a building, managing the indoor temperature is a key part of smart energy use in real life. There are many solutions for this in both decentralized and centralized heating solutions, such as Tampereen Energia's SmartNRG Heat Control.[78]

Energy production in buildings

One of the strengths of a district heating network is that it enables centralized and efficient operation, which eliminates the need for many building-specific solutions. The larger the thermal storage, the more affordable it is. There is no need for building-specific hot water heaters when heating energy is stored in large thermal stores. The same applies to auxiliary electric heaters. In addition to economies of scale, centralized implementation benefits from the energy company's minute-level optimization ability.

There are many ways to optimize energy use in buildings that we are not aware of. Energy solutions can be evaluated against district heating pricing in Tampere, which is based on the cost-effectiveness of centrally produced heat. If, for example, a hybrid solution proves profitable, it is likely to make sense from the perspective of the entire system – and if it is not, investing in it is probably not justified. The power of cost-effective pricing is that builders and designers can look for creative, energy-efficient solutions guided by the actual cost structure.

5.12 Combined technologies

Some technologies work poorly alone, but well combined other technologies. For example, heat pumps work with a higher efficiency, the warmer the water they produce or the higher the heat source they use. While some plants, by their nature, produce hotter water than a district heating network requires. A combined solution is probably the most viable option in the transition phase to completely combustion-free heating or in systems using combustion together with carbon dioxide recovery.

Geothermal, solar thermal, lake thermal and air-to-water heat pump solutions can only work in practice in conjunction with other heating plants or as part of a low-temperature network. The waste heat recovered by heat pumps is also so lukewarm that the water must be heated to the temperature level required by the district heating network, i.e. it must be primed. Solutions that do produce sufficiently warm water are electric boilers and combustion-based heating systems.

Combining technologies can also pose problems, because the plant that produces the lower temperature water is dependent on the priming plant. This is a challenge, especially if an electric boiler is used for priming, because it would not be desirable to use it when electricity prices are high. A combined solution is also a more complex option. However, using combined technologies is essential to minimise the limitations and disadvantages of different forms of production.

[78] tampereenenergia.fi/energiaratkaisut/lammonohjaus/

6 Tampereen Energia's production scenarios

This chapter presents a combustion-free production model based on electrification of Tampere's district heating production (Waste and Surplus scenario) and a carbon dioxide capture option (BECCU scenario) for the year 2040. In addition to these two main scenarios, a few other alternative scenarios have been considered. These alternative scenarios for heating Tampere take into account the boundary conditions found earlier in the study for the utilization of the electricity system in heating. In summary, we can compare the district heating system to fully electric heating.

In our examination, we have taken into account the internal assumptions required to implement each production scenario. The aim of writing these assumptions out in detail is to present the kind of changes that are needed in the operating environment.

It is important in the scenarios that emissions are not outsourced outside the scope of the examination, but that the entire energy system is functional and low-emission. The aim of the scenarios is to:

- be enable us to compare alternatives at the system level. A solution may seem implausible overall, but may be internally consistent.
- understand how much public investment is required to achieve the result.
- visualize the scale of the proposed technologies, so that it is easier to understand the strengths of different technologies and the challenges posed by fluctuations in heat demand.

Detailed profitability calculations far into the future do not serve the study's goal, which is to increase understanding of production challenges. The affordability of each scenario depends on the price assumptions used, which are affected by, among other things, taxation of electricity use and wood energy use. If a tax is imposed on these, using electricity in heat production or capturing carbon dioxide from bioenergy will not be attractive. Since electricity is used in all scenarios, it has been assumed that there will be overproduction of electricity from time to time, i.e., surplus electricity will be generated, which will make the use of electricity in heating profitable.

Energy policy will play a key role in selection of future heating solutions

Electricity price forecasts also introduce uncertainty into the calculations. Electrification and the increase in wind power have brought high peaks and zero prices to prices. Estimates for the size of price peaks and the number of zero hours vary in different forecasts. During high price peaks, the needed electricity can be produced by combusting fossil fuels, which is inefficient, either in neighbouring countries or in Finland. In these situations, burning wood – and in some cases even fossil fuels – to produce heat for short periods, both of which have higher efficiency, is better than using electricity.

Despite the uncertainties of the future, we can present investment costs for different scenarios. If a plant is discontinued, it will not require maintenance investments. We have not attempted to estimate these costs in this work, so the investment costs we provide only give rough size ranges. Detailed profitability calculations are always made on a case-by-case basis. Looking at investment cost alone is not enough, but it can provide a useful perspective on the challenge. A more expensive transition is a slower transition.

In the 2025 update, the production structure of the scenarios has been simplified so that each scenario deepens the understanding of the challenges and opportunities in a specific operating environment. In addition, the scenarios take better account of the fact that non-combustion energy is not available from the electricity system during severe frosts.

Table 10. Overview of the different scenarios and the purposes they serve.

Scenario	Why is it in the report?
Waste and Surplus	Describes the maximum potential of waste heat and surplus electricity in the district heating network.
Nuclear District Heating	Describes an option where no waste heat is available, but there is also no combustion in the heating system.
Minus	Describes a situation where only a little waste heat has been generated and the demand for district heating has fallen by -40%.
BECCU	Describes a waste heat source generated through carbon dioxide capture.
Without District Heating	Describes a heating system where district heating is completely abandoned.

Initially, the scenarios included Tammervoima as one form of heat production. The only alternative to incinerating non-recyclable waste would be to dump it in landfills. From this perspective, the heat generated from waste incineration can be considered waste heat. Waste incineration was already discussed in detail in Chapter 5.10.1. If recycling increases significantly or if it is decided politically, the heat from Tammervoima could be replaced by other technologies. This option is examined in the Nuclear District Heating scenario.

The main challenge in these scenarios is naturally the high heat consumption in winter, when some non-combustion-based technologies are not available. Heating with electricity is not combustion-free unless electricity production is combustion-free at that time. As we discussed in Chapter 2.2, we do not believe it is feasible that Finland's electricity production can be combustion-free during a peak consumption situation in 2040. Auxiliary electric heaters are not suitable for combustion-free power in freezing temperatures. Therefore, seasonal thermal storage has been added to the scenarios for peak power production.

The waste heat in the scenarios uses electricity consistently or not at all. In our modelling, waste heat is also used in the dimensioned situation. This is a simplification of the modelling. Accurate management of the situation would depend on what kind of waste heat is available. In a shortage situation, data centres are more likely to start backup power generators than shut down the data centre. In this case, waste heat is available. Hydrogen production processes could well be shut down in a shortage situation in the electricity system. This could be managed by using district heating thermal storage. The steady electricity consumption as modelled is also very different from the electricity consumption discussed in Chapter 3. In this situation, when the district heating scenario does not generate electricity demand peaks, we believe it is justified to call waste heat combustion-free heat even during severe frosts. In the longest and deepest power shortage, district heating combustion reserve capacity could also be utilized if more combustion were needed in the electricity system.

The district heating scenarios presented in the report have been modelled with the Energy Optima 3 optimization tool. The underlying assumptions for the calculation have been the electricity price curves developed by Tampereen Energia and the predicted district heating demand curve.

6.1 Scenario: Waste and Surplus

The base sources of production in the Waste and Surplus scenario are Tammervoima and waste heat. In this scenario, waste heat includes carbon dioxide capture from Tammervoima, data centres and possibly biochar production. In this scenario, there is a hydrogen industry, but carbon dioxide capture from biomass burning has not proven to be profitable in Tampere. However, there are a significant number of data centres located in the city, whose waste heat is utilized for district heating. The key assumption in this scenario is that in winter 2040, waste electricity will still be regularly available for electric boilers.

The competitive advantage in the scenario is the utilization of waste heat and waste electricity. In a centralized system, heat production can be economically optimized in real time. This makes it possible to avoid using electricity when it is in short supply, which helps maintain the balance of the electricity system compared to decentralized electric heating. Excess waste heat in the summer can also open up opportunities for a growth strategy – this could also be done in Tampereen Energia's district cooling system by applying absorption heat pumps.

The plan maintains a third of the current capacity for combustion-based production. However, these produce 0% of the energy in the scenario. Depending on the cleanliness of the electricity system, the actual figure would be somewhere between 0–5%. Combustion is only needed in the heating system if more is needed in the electricity system. This can be used to prevent, for example, escalation of disturbances in the electricity grid. If combustion-free plant investments are increased compared to this plan, costs will increase, but combustion will not decrease. The need to maintain plants in reserve for the sake of supply and security of supply illustrate the technical and economic challenges of power management well.

The total capacity is designed to be 680 MW + reserve capacity, and the investment costs are approximately EUR 509 million. Air-to-water heat pumps are dimensioned so that they do not operate at temperatures below -8°C, and therefore they are not calculated as increasing production capacity. Since the goal is a non-combustion system, and the electrical system is not combustion-free in extreme cold, electric boilers are not included in the available capacity. Heat pumps required for waste heat recovery have been included as an investment.

Carbon dioxide capture serves sectors other than heat production and electricity production, and therefore investment in it has not been included in this as an investment in the energy sector. The captured carbon dioxide is also not allocated as negative emissions for heat production in the emission calculation, but as an emission reduction in, for example, the transport sector.

According to previous studies by Tampereen Energia, the investment in carbon dioxide capture equipment at the Naistenlahti power plant would be approximately EUR 1.18 million / ktCO2 including carbon dioxide liquefaction. Scaling this estimate, Tammervoima's full-capacity capture equipment would therefore cost approximately EUR 212 million. However, the availability of carbon dioxide and the possibility of recovering waste heat on the same plot make the process significantly more efficient than carbon dioxide capture at another location. A cheaper transition is a faster transition. The costs of carbon dioxide capture have been excluded from the table below, since it only includes investments related to the actual transition in the heating sector.

Production plant	Power	Investment
Tammervoima	56 MW	0
Waste heat	224 MW	€ 224 million
Air-to-water heat pump	50 MW, calculated 0% for the design capacity	€ 50 million
Thermal storage	400 MW	€ 230 million
Electric boiler	192 MW, calculated 0% for the design capacity	€ 5 million
Reserve power	300 MW	0
Total	680+300 MW	€ 509 million + CCU
Thermal storage total	91 GWh	
Carbon dioxide capture Tammervoima	180 000 t/year	
Carbon dioxide capture Naistenlahti 3	0 t/year	

Table 11. Production output and investment costs in the Waste and Surplus scenario.

Scenario assumptions

1. There is demand for district heating, meaning it is competitive against building-specific heat pumps. This will happen if there is good availability of waste heat and the price is sufficiently low, and competing solutions are not heavily subsidized.
2. The amount of waste heat available is increasing rapidly.
3. Heating solutions that rely on electric heating during electricity shortages will have to pay the costs they cause to the electricity system based on the polluter pays principle.
4. Heat pumps and electric boilers combined with seasonal thermal storage are a more competitive way to produce district heat than the Naistenlahti 3 biopower plant and the carbon dioxide capture that might be connected to it. This may be influenced, for example, by the demand for synthetic fuels or the cost or regulation of carbon dioxide capture.
5. Non-recyclable waste is generated and its incineration is acceptable when combined with carbon dioxide capture technologies.
6. The production of synthetic methane from waste incineration flue gases based on carbon dioxide capture is a profitable business. The heat released from hydrogen electrolysis can be utilized as waste heat.
7. There are suitable locations in the city for industrial-grade air-to-water heat pumps and the technology proves to be a reliable way to produce heat in both warm and cool seasons.
8. Surplus electricity for electric boilers is available.

9. There is no electricity tax on electric boilers and heat pumps or the electricity tax is at the EU minimum tax level. The electricity transmission price for electric boilers is reasonable.

10. The electricity transmission network can withstand an increase in electricity consumption on a windy winter day. If surplus electricity is available but cannot be transferred to Tampere, the simulated use of electric boilers is not realistic.

11. Fingrid is building a new grid connection to Nokia to transfer the necessary electricity for the use of waste heat, heat pumps and electric boilers.

12. Tampere has sufficient space for seasonal thermal storage.

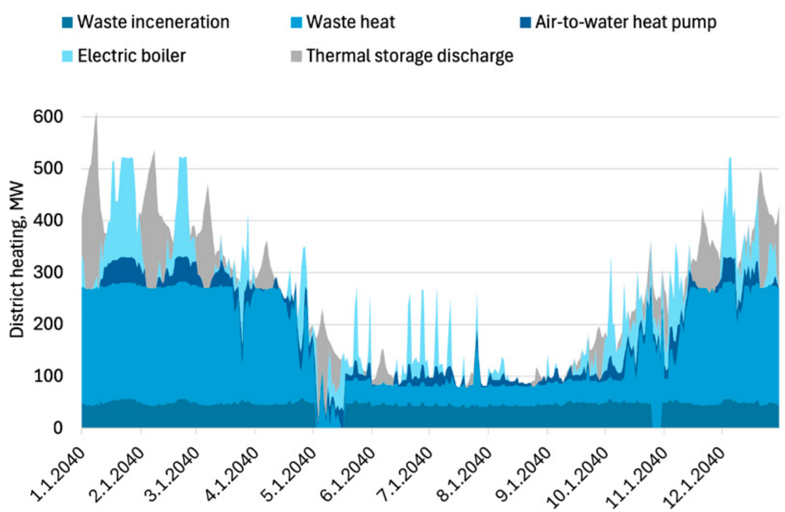


Figure 34. The production structure in the Waste and Surplus scenario. In this figure, the x-axis is time (one year with daily resolution) and the y-axis is the district heating demand as average daily output.

Roadmap to reach the scenario

To achieve the Waste and Surplus scenario, most of the current production must be replaced with something new. Some of the investments can be easily and quickly implemented, others require a longer-term approach. Possible roadmap to reach the Waste scenario in 2040:

1. Nokia will receive a new Fingrid grid connection in 2028, from which a connection to Tampere will be built in 2029.

2. Installing a new electric boiler is simple and can be done quickly, and probably connected to a thermal storage facility.

3. The introduction of large cave thermal storage should be tied to the availability of waste heat and the shutdown of combustion-based heat production. As long as combustion-based CHP is needed in the electricity market, it is worth managing electrical power by alternating electricity production and electricity consumption. When combustion is stopped, this is no longer an option, and a large thermal storage facility will be necessary to manage electricity availability and price fluctuations.

4. In the scenario, waste heat is based in particular on data centres and, to a lesser extent, biochar. Currently, interest in building data centres is high. The surprising plan to increase the electricity tax on data centres has cast a shadow over this boom. The profitability of biochar production determines the profitability of this waste heat source. Once this is resolved, operations can be expanded rapidly. The amount of waste heat is therefore likely to increase gradually as we approach 2040. The availability of waste heat is a key uncertainty for the realization of this scenario.

5. Air-to-water heat pumps can be designed and installed as needed, when profitability looks good.

6.2 Scenario: Nuclear District Heating

If bioenergy does not play a role in the future energy system or in the implementation of technical carbon dioxide capture, and at the same time the growth of waste heat does not materialize as expected, nuclear district heating will remain an important backup plan. It has the potential to become a better solution to the triple energy problem in heating than stand-alone systems. This scenario illustrates how a combustion-free scenario can be achieved without waste heat. The expensive investment and low operating costs mean that nuclear district heating provides the base and medium load. In the scenario, the rest of the demand is produced by other non-combustion-based alternatives.

The benefits of nuclear district heating are the high available power, stable production and zero emissions. Notably, when combined with district heating thermal storage, nuclear district heating is also able to adjust production according to need. The obstacles to nuclear district heating include the high investment costs and the fact that there is, as yet, no construction experience. This results in deficiencies in regulation, expertise and especially practices. We do not doubt that Finland has the theoretical expertise to build a safe plant. However, the first plant is always the most difficult. As in all human activities, repeating the work will improve efficiency and reduce costs.

Since there is no waste heat used in the scenario, 250 MW of nuclear power has been modelled for it. Since many of the costs of nuclear power are already realized when the first megawatt of nuclear power is built, 200 MW of nuclear power is a more realistic amount for Tampere than, for example, the 50 MW in the previous study. Since each additional unit is relatively cheaper than the previous one, we believe that nuclear district heating can be competitive during the presented peak operating hours. Heat production in summer is easy, so the profitability does not depend on whether nuclear power can replace other cheap heat production in summer. What is crucial is the price of the heat production it replaces in winter.

The investment costs in the scenarios are mainly based on investment decisions that have been implemented. Nuclear power is a significant exception to this. No nuclear district heating plant has been built, so the level of cost is more speculative. In industry presentations, the investment cost of a 50 MW plant has been estimated at EUR 100 million. This is about twice the cost of industrial heat pumps and more expensive in terms of investment costs than a geothermal system for the customer. The operating costs are of course lower and the service life is long, but this indicates that the more expensive nuclear power plants presented here cannot, or will not, be competitive.

As can be seen from the table and graph below, a functioning energy system requires much more than just nuclear power plants, including adjustable heat production using electric boilers and thermal storage. This whole system must be more cost-effective than a ground-source system for the customer. A system that is too expensive is a system that has no customers.

Production plant	Power	Investment
Nuclear reactor	250 MW	€500 million
Waste heat	0 MW	
Air-to-water heat pump	50 MW, calculated 0% for the design capacity	€ 50 million
Thermal storage	400 MW	€ 230 million
Electric boiler	192 MW, calculated 0% for the design capacity	€ 5 million
Reserve power	300 MW	
Total	700+300 MW	€ 785 million
Thermal storage total	91 GWh	
Carbon dioxide capture Tammervoima	0 t/year	
Carbon dioxide capture Naistenlahti 3	0 t/year	

Table 12. Production output and investment costs for the Nuclear District Heating scenario.

Scenario assumptions

In contrast to the non-combustion Waste and Surplus scenario, it is assumed that:

1. all combustion is very expensive, so it is not worth continuing to use the current plants. However, the district heating reserve capacity is maintained as in the other scenarios.

2. no waste heat is available in Tampere at all.

In addition, it is assumed that:

1. nuclear district heating can be built safely in Tampere.

2. there is clear political approval for nuclear district heating and regulation enabling its implementation.

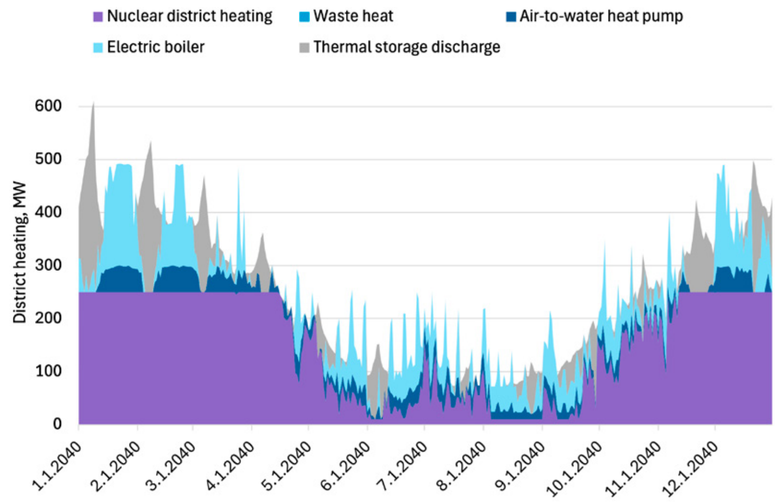


Figure 35. The production structure for the Nuclear District Heating scenario.

6.3 Scenario: Minus

The last of the combustion-free scenarios deals with a situation in which the district heating network is reduced, i.e. heat production is shifted from centralized to house-specific solutions. This requires that district heating has lost its competitiveness for a long time between now and the year under review. In the scenario, the demand for district heating has decreased by 40% compared to the Waste and surplus scenario.

This means that the current district heating production plants and transmission network will remain underutilized and the turnover of energy companies owned by the cities will decrease. This will lead to a decrease in tax revenues and dividends and a decrease in the value of the city's assets. Tampereen Energia is the largest payer of dividends in the city of Tampere. For example, in 2023, Tampereen Energia paid the city of Tampere EUR 20 million in dividends, which was 76% of all city dividend income.[79]

The shift to building-specific solutions will increase the investment needs of heat customers and raise the costs of electricity power management and electricity network maintenance. In the Minus scenario, the losers are both cities and heat customers. The winners are equipment manufacturers and design offices. In Chapter 3.5, it was estimated that a 100% transition to ground-source heating would require an investment of EUR 2.6 billion. This means that the 40% transition considered in this scenario would require an investment of EUR 1.0 billion in the electricity system. There will also be some need for combustion for peak management in the electricity system. This has been discussed in Chapter 6.5 and the impact on this scenario has been collected in a summary table in Chapter 6.6.

The scenario assumes that less waste heat will be generated and later. With the demand shifted to the electricity system, thermal storage that is half the size will be sufficient to cover a cold period. The discharge capacity has been reduced by 100 MW. The assumption is that carbon dioxide capture from Tammervoima is implemented.

Production plant	Power	Investment
Tammervoima	56 MW	0
Waste heat	72 MW	€ 72 million
Air-to-water heat pump	50 MW, calculated 0% for the design capacity	€ 50 million
Thermal storage	300 MW	€ 115 million
Electric boilers	142 MW, calculated 0% for the design capacity	€ 5 million
Reserve power	300 MW	0
Total	428+300 MW	€ 237 million + CCU + € 1 000 million Electricity system
Thermal storage total	46 GWh	
Carbon dioxide capture Tammervoima	90 000 t/year	
Carbon dioxide capture Naistenlahti 3	0 t/year	

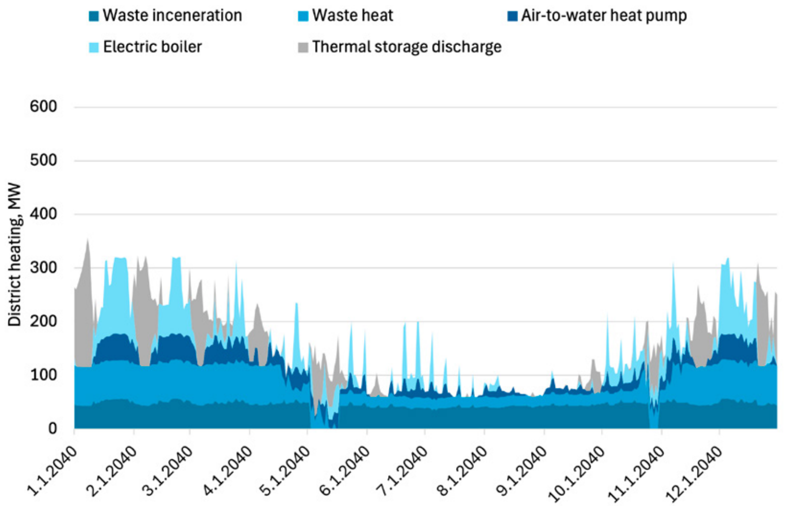
Table 13. Production output and investment costs for the Minus scenario.

[79] Raportti Tampereen kaupungin tytäryhtiöiden toiminnasta vuodelta 2023

Scenario assumptions

In contrast to the combustion-free Waste and Surplus scenario, it is assumed that:

1. District heating has lost its competitiveness for a long time between now and the year under review. Demand for district heating has decreased by 40%.
2. The availability of waste heat has been low or has been realized late – while waiting for it the price of district heating has been high and the loss of customers has been significant.



Kuva 36. The production structure of the Minus scenario.

6.4 Scenario: BECCU

In this scenario, carbon dioxide capture systems have been added to Tammervoima and Naistenlahti. The scenario describes a situation where large quantities of synthetic fuel are produced in Tampere. This requires carbon dioxide from renewable sources and produces significant amounts of waste heat. The amount of captured carbon dioxide is so large that some of it can also be directed to permanent storage as the infrastructure and markets develop. However, due to the use of carbon dioxide, this scenario describes a positive carbon footprint from district heating rather than systemic carbon negativity, although there are also future opportunities related to storage.

In this scenario, only small investments are needed in the energy system, because existing equipment can be utilized and the investment money comes from outside the energy sector. In this scenario, the district heating system enables emission reductions in the transport sector.

The Tammervoima utility power plant and the Naistenlahti 3 biopower plant provide the base loads with carbon dioxide capture, and the rest of the demand is produced with heat pumps and electricity. The technologies included in the scenario are thermal storage, waste heat from synthetic fuel, waste heat from data centres, and electric boilers. The need for electricity-based heat production is lower than in the above combustion-free scenarios.

The benefits of the BECCU scenario are the large positive climate impact of district heating on other sectors and greater support for the electricity system. Naistenlahti 3 and Tammervoima both produce both electricity and heat, which increases the efficiency of the system and improves controllability. The use of the Naistenlahti power plant also reduces the need for reserve power and makes the need to rely on it less frequent.

The equipment required for carbon dioxide capture is so expensive that it cannot be in operation for half of the year. Therefore, the plants operate as base loads. Only investments directly related to energy production have been added to Tampereen Energia's investments. According to previous studies by Tampereen Energia, the carbon dioxide capture equipment for the Naistenlahti power plant would cost approximately EUR 1.18 million/ktCO_2 including carbon dioxide liquefaction. Scaling this estimate, the full capacity of the Tammervoima and Naistenlahti power plants would cost approximately EUR 566 million.

The implementation of carbon dioxide capture depends on whether it is a profitable business. Investments in the transport sector would be significant here, as the construction of synthetic fuel production plants (electrolyzers, methane production units, liquefaction units, refuelling stations, etc.) would require significant capital, but these investment costs should not be added to the comparison as energy system costs. District heating acts as an enabler in the scenario. District heating customers cannot be asked to pay for emission reductions in the transport sector.

Production plant	Power	Investment
Tammervoima	56 MW	
Naistenlahti 3	230 MW	
Waste heat	124 MW	€ 124 million
Thermal storage	400 MW	€ 230 million
Electric boilers	142 MW, calculated 0% for the design capacity	
Reserve power	200 MW	
Total	710+200 MW	€ 372 million + CCUS
Lämpövarastoja yhteensä	91 GWh	
Hiilidioksidin talteenotto Tammervoima	180 000 t/year	
Hiilidioksidin talteenotto Naistenlahti 3	300 000 t/year	

Table 14. Production output and investment costs for the BECCU scenario.

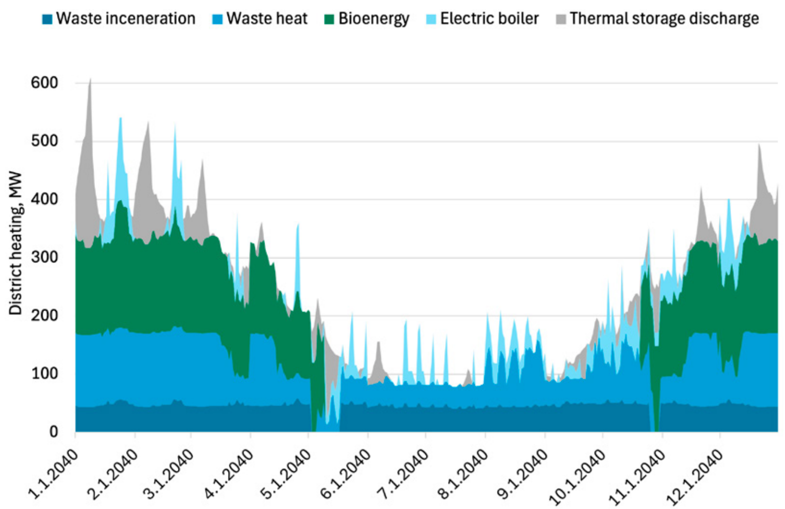
BECCU scenario assumptions

In contrast to the combustion-free Waste and Surplus scenario, it is assumed that:

1. waste heat is strongly based on carbon dioxide capture and utilization. The regulation and market mechanism for carbon dioxide capture are being successfully built to make the business profitable. The business is located in Tampere.

2. the bioenergy used is genuinely sustainable, so that when combined with carbon dioxide capture it has political approval.

3. heat pumps do not prove to be more profitable than electric boilers and production combined with carbon dioxide capture, so that no investments are being made in Tampere.



Kuva 37. The production structure of the BECCU scenario.

Roadmap to reach the BECCU scenario

Some investments can be easily and quickly implemented, while others require a longer-term approach. Here, one possible roadmap for reaching the BECCU scenario is outlined, moving from the bottom up to the production picture.

1. Nokia will receive a new Fingrid grid connection in 2028, from which a connection to Tampere will be built in approximately 2029.
2. Tammervoima's utility power plant and Naistenlahti 3 do not require any other measures than the construction of carbon dioxide capture equipment and transport logistics. This can be done, with contracts and planning, in about five years, as long as carbon dioxide capture is profitable.
3. It is worth linking the introduction of large district heating thermal storage or cave thermal storage to the introduction of waste heat, and to the phase out of combustion-based heat production that does not utilize carbon dioxide capture.

6.5 Scenario: Without District Heating

The transition to a ground-source heating system was already discussed in Chapter 3. This chapter details how the system would work. The purpose of this scenario is to illustrate what kind of challenges would arise if the heating system were built solely on electric heating. In order to utilize the results of Chapter 3, the scenario has been modelled differently from the district heating network scenarios. The scenario is based on the actual situation in 2023–2024, while the other scenarios are based on a simulated future. The purpose of this work is not to create a detailed comparison of completely optimised energy systems, but to illustrate phenomena that should be taken into account when planning heating systems and related energy policies.

If the task were to actually design and implement a heating system based entirely on heat pumps for Tampere, it would be worth also considering smaller regional networks and energy communities. We have deliberately ignored these. Currently, the transition away from district heating is not happening in this centralized manner, but individually. Thus, we see that this slightly suboptimal ground-source system best describes the current development. We have tried to make our assumptions so that the scenario is comparable to the district heating system and previous scenario modelling.

The heating season in 2023–2024 included very cold periods for the first time in a long time. The dimensioned temperatures were not exactly at the dimensioned temperature, but the period was several days long, so it can be used as a good example of a calm, very cold frost period. We use the heat pump system according to model 3 described in chapter 3, whose heat consumption is scaled to correspond to the district heating consumption in Tampere. The ground-source heat pump can produce most of the annual energy. However, when the temperature drops close to the dimensioned temperature, some of the heat is produced directly by electric heaters, as shown in the figure below.

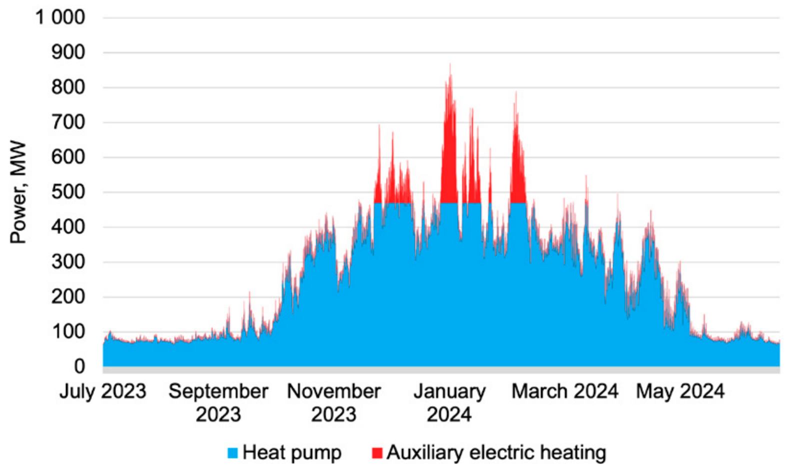


Figure 38. Tampere's heat production with building-specific heat pumps and electric heaters.

Chapter 3 examined the problem of system power output during extreme cold. Figure 39 shows the situation scaled to a city the size of Tampere. The figure shows that there are several 1–2-week periods during the year when wind power production is low. In order to make the scenario comparable to district heating scenarios, we now need to take a position on how this missing energy is produced.

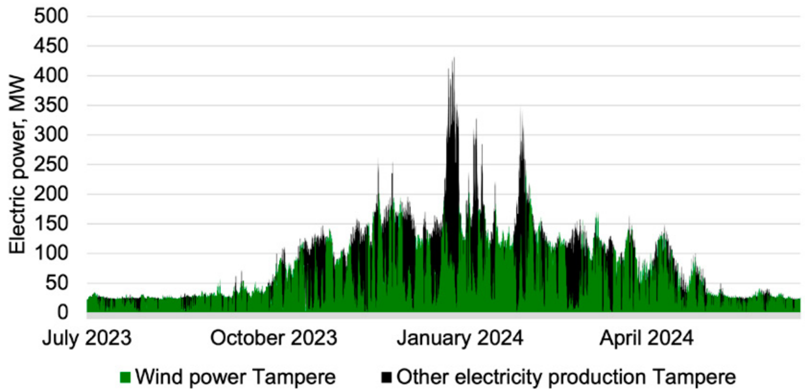


Figure 39. Electricity procurement in the Without District Heating scenario.

Our scenario is on the scale of Tampere for comparability, but it describes a situation in which district heating is abandoned in all of Finland. Tampere's power management problems would be easy to solve if the flexibility of all of Finland was in use. However, this would not be in line with our scenario. Therefore, we will briefly switch back to an electricity system on scaled to the size of Finland.

The overall need for other electricity production on the Finnish scale is 4.8 TWh (black area in Figure 39). The majority of the energy could be covered by hydropower, energy storage and demand-side flexibility. However, this is not a plausible assumption for the longest periods. The need for other electricity production according to our model is described below. We assume that the first 48 hours of an electricity shortage can be covered by the non-combustion flexibility in the system. After that, we also assume that half of the need can be covered, for example, by hydropower and demand-side flexibility. After this, there is still a need for 1.2 TWh of electricity production (Figure 40).

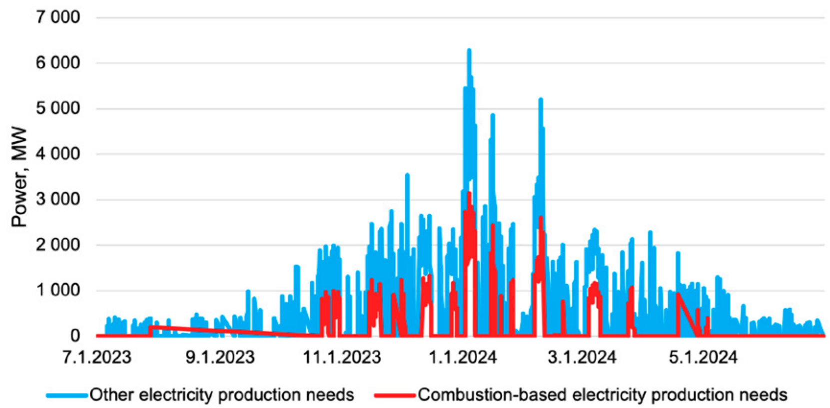


Figure 40. In addition to wind power, blue represents the electricity production needed in Finland if district heating is abandoned. Red represents the amount that requires combustion-based energy sources.

In Chapter 2.2.5, we stated that combustion-free solutions for such rare electricity production are extremely expensive. In our scenario, all district heating has been replaced with geothermal heat, so district heating CHP is not an option. This leaves combustion-based industrial CHP and condensing power generation. Maintaining these options may be profitable, because our model relies very heavily on demand-side flexibility, so the internal logic requires that the price of electricity in shortage situations is high.

The graph shows that approximately 1 000 MW would be sufficient to cover the majority of combustion-based energy. Let us assume that this would be handled by industrial CHP using bioenergy and the rest by the natural gas-burning backup power plants described in Chapter 3.2.4. This makes the amount of wood electricity 0.93 TWh and the amount of fossil-based electricity 0.28 TWh.

In 2022, 11.4 TWh[80] of electricity was produced from wood and 60.6 TJ, or 16.8 TWh, of fuel was used. This means that electricity production had an efficiency of 67%. This efficiency is high because Statistics Finland's calculations allocate a large part of the fuel to heat production. In the scenario, a total of 0.93 TWh/0.67 = 1.4 TWh of wood is used for electricity production. The backup power plants in Chapter 3.2.4 would use 0.28 TWh/0.4 = 0.7 TWh of natural gas. Natural gas emissions would be 141 000 tonnes of CO_2 per year.

Now we need to return to energy use on the Tampere scale so that we can compare the figures with the district heating scenarios. Scaled to a city the size of Tampere, 87 GWh of wood would be used, and 43 GWh of natural gas, and fossil emissions would be 8 800 tonnes of CO_2 per year.

Without District Heating scenario assumptions

1. District heating is not competitive against ground-source heating, indeed ground-source heating is the most cost-effective heating solution for customers and it is available and installed in all locations.

2. We assume that it consists of a ground-source heat pump with a COP of 3 and auxiliary electric heating.

3. The pump is sized so that the ground-source heat pump's capacity coverage in the 2023–2024 heating season would have been 70%. In this case, the energy coverage would have been 98.6%. It is noteworthy that in January 2024, the dimensioned temperature for Tampere was not used. Extrapolating to the dimensioned temperature conditions, the capacity coverage would have been a few percentage points lower, approximately 66%. A higher capacity coverage would of course be technically possible, but economically less optimal, so it would contradict assumption 1.

4. Wind power is built into the electricity system with the same annual energy to cover the increased electricity consumption. This is not a forecast, but rather an illustration of the fact that although wind power and geothermal electricity consumption correlate well at the seasonal level, when viewed on an hourly basis, there is a significant need for additional production.

5. Wind power can also produce a large part of the system's electricity needs. In times of no wind, and especially in severe frosts, the system will also have to use other sources of electricity production.

6. The transition will not only take place in Tampere, but throughout Finland.

Costs

A ground-source investment includes an investment in a ground-source heat pump, well drilling, associated equipment (such as an electric heater), piping and work. The estimated total cost for all our customers would be approximately EUR 1.4 billion. When the wells cool down, the drilling investment must be renewed or changed to another heating system. In addition, the heat pump system will require either a new compressor or replacement of the entire pump approximately every ten years. Investments in electricity production have been estimated in Chapter 3.5. The investments in wind power would be EUR 0.4 billion and in gas turbines EUR 0.4 billion.

As the rated power increases from 400 MW to 1 000 MW, investments are needed in power transformers, high-voltage distribution networks, substations, distribution transformers, medium-voltage cables, low-voltage cables and distribution cabinets. Scaled to Tampere according to Chapter 3.3, we estimate the cost of reinforcing the electricity network would be EUR 0.15 billion. In line with Chapter 3.4, we estimate the cost of reinforcing the transmission network would be EUR 0.2 billion.

The total investment cost for the transition to ground-source heating based on a small proportion of combustion in Tampere would be EUR 2.6 billion.

[80] Energian kokonaiskulutus -taulukot, taulukko 3.3

	Power	Investment
Ground-source systems	900 MWth 466 MWe	€1.4 billion
Wind power	317 MWe	€0.4 billion
Peak production	286 MWe 34 GWh	Electric battery €3.4–9.6 billion OR Gas turbine €0.4 billion
Electricity transmission	466 MWe	€0.2 billion
Electricity distribution	466 MWe	€0.15 billion
Total		€2.6–11.7 billion

Table 15. The cost of abandoning district heating in Tampere and the necessary investments in the electricity system.

Observations from the Without District Heating Scenario

1. A ground-source heating system consumes a lot of electrical power when electricity production is based on fossil fuel combustion. A ground-source heating system is therefore neither fossil-free nor combustion-free.

2. The need for electrical power in Tampere would increase by approximately 466 MW. This would require the current electricity distribution network to be more than doubled.

3. Electricity demand in Finland would increase sharply, especially during freezing weather. This would require significant investments in electricity production on cold days. According to Chapter 2.2, this new electricity production would be fossil fuel combustion in 2040.

4. Building-specific ground-source heating systems require significantly more surface area compared to centralized heat production. Even though the ground loops are underground, drilling such a large surface area in city centre areas would cause problems. Large-scale drilling limits urban development, and drilling is not possible everywhere. Wells also cool down and require significant new investments or structural changes during the life cycle of the building.

5. In a heating system based on a single technology, the increase in electricity prices is a more difficult risk to manage than in a system where it is possible to use several forms of production.

6. In a heating system based on a single technology, the reliability of maintenance and supply is weaker than in a system that can produce heat using different technologies.

6.6 Scenario cost comparison

Table 15 shows a comparison of the investment costs and emissions of the scenarios. All of the district heating scenarios examined in this study have very low emissions and the use of electricity in district heating production is scheduled so that it does not cause a burden on the electricity system.

Scenario	Emissions	Total investment*	Bioenergy use**	CO_2-capture investment	Captured CO_2
Waste	0 ktCO_2	€509 million	0 GWh	€212 million	180 ktCO_2
Nuclear District Heating	0 ktCO_2	€785 million	0 GWh	€0 million	0 ktCO_2
Minus	5 ktCO_2	€1237 million	35 GWh	€106 million	90 ktCO_2
BECCU	0 ktCO_2	€372 million	800 GWh	€566 million	480 ktCO_2
Without District Heating	9 ktCO_2	€2600 million	87 GWh	€0 million	0 ktCO_2

Table 16. Summary of scenarios.

** The comparison only includes investments related to the actual transition. Investments already made have not been taken into account. In addition, each scenario involves significant maintenance investments, but they are considered to be roughly equal in all scenarios. The current structure will naturally require investment at the end of the plant's service life. The investment figures are much simplified and, for example, the timing of investments will have a significant impact on the profitability of each scenario. The euro investment numbers in this table are at the lower end of the ranges presented in previous chapters.*

*** The use of bioenergy in the Minus and Without District Heating scenarios comes from the need for combustion in the electricity system, since a large portion of the heat consumption, previously supplied by the district heating networks, will be shifted to the electricity network.*

This chapter does not attempt to and cannot answer the question of which is the best way to produce heat for the next 50 years. The market-based implementation of carbon-negative and non-combustion scenarios still requires significant changes in the operating environment.

The competitiveness of district heating compared to building-specific solutions after investment is essential, because otherwise the end result will be a non-combustion-based heating system without customers. Alternative building-specific systems operate in the same operating environment. Based on our review, district heating appears to be very competitive compared to standalone heating solutions in all the scenarios presented.

7 Recommendations for decision-makers

Electricity should not be used for heating during peak consumption

The dimensioning situation for the heating system and the Finnish electricity system is a cold and windless week, which occurs rarely, but regularly. Financial support should not be used to even out or handle electricity price peaks, because price fluctuations are important to make sure the system works, and the market already reacts appropriately.

A cold and windless period of several days can be covered cost-effectively by thermal storage in the district heating system or by combustion-based solutions in the electricity system. The demand-side flexibility is not sufficient to cover the total energy demand of the dimensioned week. In the electricity system, the most likely technical solution would be gas turbines, because scaling up combustion-free peak power to the same scale as wind power would be prohibitively expensive. If the peak heating is transferred from the district heating system to the electricity system, the result will be a weaker emission, price and security of supply profile than there is now, i.e. a worse energy system.

Using the term "combustion-free" puts the focus on the technology, even though the net emission reduction is actually the deciding factor. For example, the combustion of hydrogen or biogas is not combustion-free, even though it is renewable and low-emission. On the other hand, electric heating appears to be combustion-free even during peak consumption situations, even though the electricity is actually produced using combustion at those times. The accuracy of the label "combustion-free" electricity changes depending on the time. Often when people say combustion-free, they mean bioenergy alternatives. The discussion will be clearer if we can avoid euphemisms.

The issue to be resolved is the electricity peak consumption situation, so we should aim for power-based demand charges and possible support measures to reduce our current consumption and increase production during peak hours.

Flexibility must be taken into account in regulation of the electricity system

The Finnish electricity system is built around stable nuclear power, variable wind power and the regulation capacity of hydropower. Finland's competitive advantage is inexpensive wind power. To maximize this competitive advantage, flexible consumption is needed. District heating electric boilers utilize surplus wind power production and respond quickly to the needs of the electricity grid. Data centres and hydrogen production consume electricity more evenly, while remaining flexible in times of scarcity.

The flexible electricity demand created by district heating, hydrogen production and data centres balances the electricity system and also enables new wind power investments in Finland. Flexible demand is activated when the price is low and, importantly, when it creates a base price for the electricity. The more flexible demand that can be located in Finland, the better the Finnish energy system will function. When it is located along district heating networks, Finnish cities will be heated with minimal environmental damage.

Data centres are usually equipped with backup power generators in case of power cuts. This can mean thousands of megawatts of backup power. However, environmental permits often limit the use of the generators in the electricity market. It is worth harnessing this largely unused capacity for power management. Their use would still be low, but utilizing devices that are already installed would save significant costs.

The opportunities to create flexibility with electric boilers, hydrogen production and data centres must be ensured.

It is worth ensuring the adequacy of electrical power with the help of district heating systems

According to studies (ENTSO-E), electrical power is running out in the dimensioning situation and this requires a response. It matters whether the solution worsens or prevents a power shortage due to heating. If sufficient electrical power cannot be ensured on market terms, a cost-effective support mechanism will be needed, such as a strategic reserve, scarcity pricing or a capacity market that is technology-neutral, competitive and tied to CO_2 limits. Allowing the price of electricity to fluctuate more during a power shortage via scarcity pricing is permitted in the EU and is a desirable solution. There is an upper limit to the price, in which cyclical power outages become more economically advantageous, and it is EUR 8 000/MWh. Therefore, mechanisms that are clearly more expensive than this should not be built.

We have identified only a few reliable types of power production that are below this cost limit, in addition to condensing gas turbine and engine power plants. One of the rare examples is the remaining gas- and bioenergy-based CHP production, and at its simplest, halting the phase-out of these would be a cost-effective measure to slow down the deterioration of the power situation. Direct support for CHP within the framework of EU rules is challenging. Nonetheless, in Germany there is talk of investing billions of euros in district heating. Germany has earmarked EUR 3.5 billion for the expansion of district heating networks by 2028.[81] The underlying motive is to reduce the use of gas, and to support the electricity system by using district heating and making use of waste heat.

The list of technologies capable of generating power shows that in the dimensioned situation, covering peak and reserve power in the electricity and heating systems is impossibly expensive without a gas system. The use of gas in Finland has decreased, but its importance for providing power is critically high. It is worth taking good care of the gas system, even though consumption is falling. The moderate total volume and the entry of renewable gases into the market mean that the emission impact of using gas during peak consumption situations is small. Gas also enables the utilization of a large amount of wind power.

Bioenergy supports flexible electricity consumption in the district heating system. The use of bioenergy in district heating is currently decreasing as the proportion of waste heat and electricity increases on market terms, which contributes to the sustainability of bioenergy. Bioenergy continues to play a major role in heating as an enabler of flexible electricity use. Bioenergy supports the transition away from fossil fuels and enables carbon dioxide capture in the future.

If public subsidies are required to ensure sufficient electricity output, the potential district heating to support the electricity system must be recognized and utilized to minimize costs.

Money for power management must be collected on a cost-causation basis

Resolving the power shortage will incur costs. The costs should not be shifted to electric boilers that utilize waste electricity or to flexible industries, such as data centres with backup power generators or hydrogen production. This kind of indirect support for electricity consumption, which is contrary to the cost-causation principle, steers both the electricity and heating markets in the wrong direction. Support for inflexible electricity consumption should also not be accepted.

With stand-alone electric heating solutions, electricity consumption peaks during extreme cold. The electrical power needed by district heating electric boilers, in turn, occurs during wind power overproduction situations. In covering the costs arising from power management, solutions that cause the need for investment must be identified and the management must be able to address these. Cause-based pricing must therefore be based on actual consumption during extreme cold, not on the use of cheap electricity.

There are two different dimensioning situations for electricity transmission: consumption during extreme cold and utilization of surplus electricity during

[81] Germany needs €43.5 bln district heating investment by 2030 to meet climate goals – report

windy weather. It is important that both cases are identified and kept separate when planning power-based demand charges. Limiting the transmission of wind power during mild weather can be managed with regulation changes and market mechanisms, but running out of power during extreme cold cannot. The flexible heating sector can be utilized on a contractual basis to reduce the reserve of transmission capacity. It is not advisable to develop the electricity network so much that all electric boilers could run in all situations.

The measures needed to address the power shortage should be funded by inflexible consumption during peak load situations.

Construction must not guide energy policy

Construction regulations are becoming stricter to achieve energy efficiency and low carbon goals, which is a good. However, the tools used in construction regulation are inevitably too crude: they lock in mistaken assumptions and distort the heating market. The biggest distortions at the moment are the E-value and the implementation of the Energy Efficiency Directive.

The purpose of the E-value was originally to provide additional information to property buyers, and to set a minimum level for the energy efficiency of new buildings. The E-value does not describe actual emissions or actual consumption, but rather the purchased energy calculated based on standardised usage conditions, and adjusted using weighting factors. Today, construction is permitted in class B or A. The role of the E-value has grown larger than the original legislation intended, because sustainability work and the conditions of green loans have become tied to it.[82] The calculation of the E-value therefore has a concrete impact on competition between different forms of heating. Another example of regulation not required by law is that Tampere requires that plots for company-owned apartment buildings meet A-level energy performance standards.[83]

The current calculation method of the E-value gives indirect support to inflexible electricity use, as it strongly encourages investments in building-specific heat pumps. The most important principles for achieving energy policy goals, such as emission reductions, are technology neutrality and competitiveness. The current system encourages optimizing the energy class, but the regulation actually guides the choice of heating solutions without having any real impact on emissions. The factors used in the calculations do not take into account regional differences in district heating or the hourly variation in electricity use for stand-alone heating systems and their harmful effect on consumption peaks.

The regulations (including energy type coefficients and requirement level) are being updated in the implementation of the reform of the Energy Performance of Buildings Directive (EPBD). The E-value should be developed to describe the technical energy efficiency of a building and to put different heating methods on an equal footing.

- EED (Energy Efficiency Directive, 2023/1791/EU): An EU directive that sets binding targets and obligations for member states to improve energy efficiency, including defining criteria for "efficient" district heating and cooling.
- EPBD (Energy Performance of Buildings Directive, 2024/1275/EU): An EU directive that regulates the energy performance of buildings and requires that new and significantly renovated buildings be zero-emission under certain energy source conditions.

The EPBD, which regulates the energy efficiency of buildings, may prevent buildings from being connected to district heating if the network is classified as "inefficient" in accordance with the EED. The intention is to define efficiency on the basis of a gradually increasing emission factor, which is good in itself, but the calculation of the factor is based on incorrect assumptions. A large proportion of the fossil emissions from district heating, and in the future almost all of them, come from waste incineration, which is in practice required by law (chapter 5.10.1).

[82] Aktia toi markkinoille vihreän asuntolainan

[83] Tampereen kaupungin asunto- ja maapolitiikan linjaukset 2022–2025

The Commission's Interpretative Guidelines[84] on the Energy Efficiency Directive emphasise the importance of utilising waste heat. If the interpretation of waste incineration is not changed, however, the implementation of the directive may prevent customers from connecting to district heating networks that utilise this waste heat. The problem is highlighted in Vantaa, where a large amount of the waste from the Helsinki Metropolitan Area is incinerated. In municipal emission calculations, emissions are not allocated to the waste producer, but remain a burden on the municipality that processes the waste. Thus, for example, Helsinki and Espoo would not need to take measures to improve recycling, as the waste treatment problem is only visible in Vantaa. The same problem applies to several Finnish cities, such as Tampere, where municipal waste is treated centrally. The contradiction is described below.

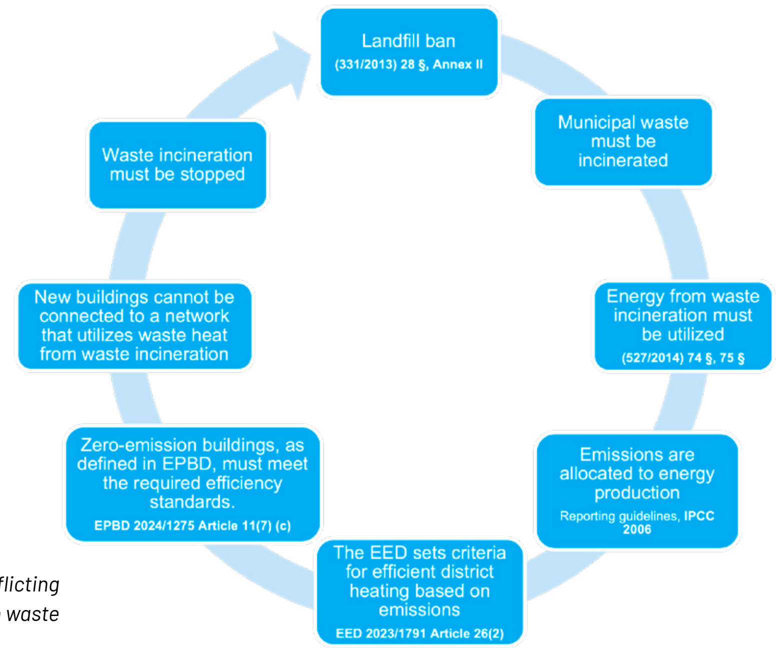


Figure 41. Conflicting regulations on waste incineration.

The contradictions depicted in Figure 41 are still being worked out in the legislation. The contradictions need to be corrected in the implementation. In Germany, waste incineration is treated as waste heat, and the same approach should also be applied in Finland. Customers need to report decreasing emissions in their sustainability work. Currently, when emissions from waste incineration are passed on to customers via district heating, this encourages companies to move away from district heating that utilizes waste heat. This will not reduce waste incineration, but the waste heat will remain unused. Even if the national emissions calculations do not change, at least district heating customers should be able to report waste heat from waste incineration as emission-free. The first step would be to amend the Guarantees of Origin Act so that a plant that incinerates non-recyclable waste could obtain guarantees of origin for the heat it produces.

There are effective tools for reducing emissions in the energy sector, such as emissions trading and excise duty, which enable flexible and precisely targeted control. The purpose of building regulations is to ensure the technical energy efficiency and life-cycle sustainability of buildings, not to steer the direction of the entire energy system.

Building regulations alone will not result in good energy policy – the goals may become self-defeating.

[84] eur-lex.europa.eu/eli/reco/2024/2395/oj/eng/pdf

8 Short summary

The most pressing question from the energy system perspective is how to resolve the growing need for power management in the electricity system in a way that is as low-emission and cost-effective as possible. To address the original assignment – how to build a combustion-free heating system – we first need to answer how we can resolve the power problem in the electricity system, on which non-combustion heating relies. Resolving this question could disrupt both the electricity and heat markets in Finland.

A heating system that relies on electricity during extreme cold does not lead to combustion-free heating. Electricity consumption peaks are not combustion-free, even though electricity is low-emission for most of the year. Efficient use of clean electricity requires a lot of flexibility, and this is precisely what a district heating system offers thanks to its minute-level control capability and existing reserve power. Storing wind power in large district thermal storage systems is the most cost-effective way to convert energy into power.

There are only a handful of affordable technologies that can solve the power problem in the electricity system, but district heating systems can reduce costs, and this is a particular strength for Finland when it comes to managing the power challenges of wind power. District heating will be integrated into the new structure created by the green transition of the electricity system through both production and consumption. District heating systems will help to both support and utilize new electricity production that varies depending on the weather.

The closer we move to carbon neutrality, the more expensive it is to implement emission reductions. The challenge of removing the last tons of carbon dioxide cannot be easily solved by relying on electricity, even with the heating coefficient of geothermal heat. On the city scale, the price and emissions from heating would jump sharply upwards due to the power problem. Instead of wrestling with the problem of the last few tons, the next stage should focus on technological removal of carbon dioxide at the industrial level, which will allow emission-reduction measures to remain significant at a truly effective scale.

The start of this phase is linked to international climate policy. The EU has already lost industrial business to countries with lower energy costs, and its ability to impose new obligations that create a business model for carbon capture depends on the voters. Nonetheless, bio-based carbon capture has a great potential to reduce emissions in Finland. Carbon negativity achieved this way is still expensive, but if there is national and international will, it is clearly cheaper to do and more effective in climate work than achieving complete non-combustion.

9 Appendices

9.1 The Nordic electricity market model

The amount of flexible electricity generation capacity in the electricity system has decreased, and political concern about the situation has increased. Various support mechanisms have been proposed as solutions, and the assessment of their strengths and weaknesses requires a review of the Nordic energy market model.

In the Nordic energy-only electricity market model, payment is made only for the energy supplied. The strength of the energy-only model is the low total cost of electricity, as the customer does not have to pay for unnecessary excess capacity. An alternative to the energy-only model would be to also pay for the capacity, which would be called a capacity market. In the capacity market, a power plant receives payment for its readiness to produce electricity, in addition to the electricity produced. In a capacity market, the availability of sufficient electricity capacity can be ensured centrally. The strength of the capacity market is therefore high security of supply even in exceptional circumstances. However, the capacity market includes the weaknesses of a centrally controlled system. The central planner typically purchases too much electricity, which means that the lifespan of the old, most polluting power plants is extended longer than is actually be necessary. This increases the average cost of electricity. For this reason, the energy-only model, which has been used in Finland since the late 1990s, has been considered the best alternative.

However, the energy-only model also has its weaknesses. It has been shown in academic literature that in a theoretical situation, if demand is inelastic and production always sets the price of electricity, the energy-only market model leads to an electricity shortage. Since only the energy supplied is paid for, the price of electricity can at most be the price of the most expensive form of production. In an energy-only market, offers must be priced according to variable production costs, of course including a risk premium for, for example, plant start up and maintenance. In this simplified situation, the owner of the most expensive form of production will never receive a sufficient margin to pay for their investment. This causes peak production to be reduced. If the market model is not changed, this will lead to a situation where electricity repeatedly run out.

As a very simplified example, imagine an electricity system with two types of power plants. Let's assume that nuclear power plants have a variable production cost of EUR 10/MWh and gas turbine plants have a production cost of EUR 100/MWh. In this simple model, the price of electricity is always either EUR 10/MWh or EUR 100/MWh. In this model, the owner of the gas turbine never makes a profit. When the gas turbine is running, they get money from the electricity they produce, but it all goes to purchasing fuel and other variable costs, such as taxes. Eventually, the owners of the gas turbine plants run out of money and the plants are closed. After that, whenever the nuclear power plants cannot not produce enough electricity, electricity simply runs out.[85]

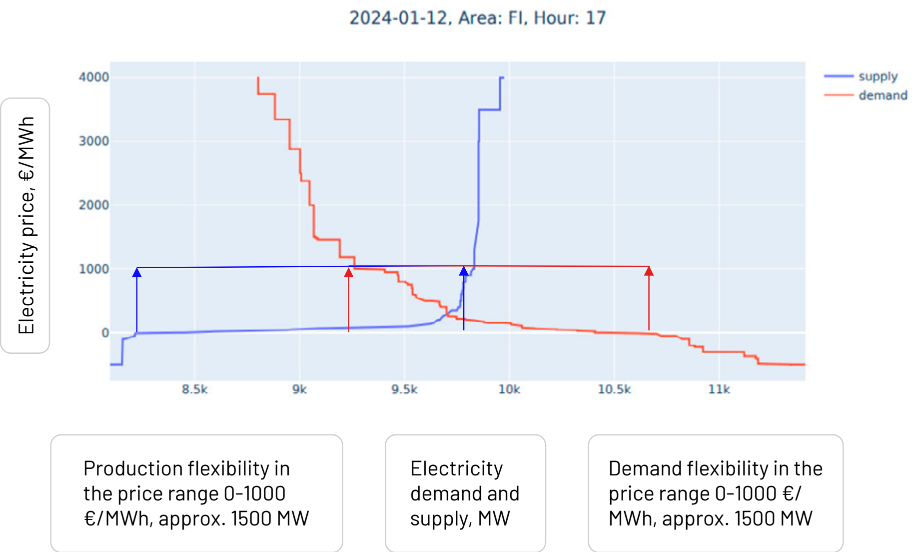
In the real system, there are many more price ranges, and the relative profitability of the different forms of production varies over time. As prices change, due to political interventions and as technology develops, more new production is built, so the conditions leading to a power shortage are not as straightforward as in our simple example. This kind of changing situation has existed in the Nordic countries for decades. When the energy-only market began, there was quite a lot of excess electricity generation capacity. The construction of wind power was first supported and then it was largely built on a market basis.

However, the complexity of the real situation merely hides the tendency towards a power shortage, it does not eliminate it. The tendency towards a power shortage is a built-in feature of the energy-only model if demand is inelastic. However, demand-side flexibility that grew significantly during the energy crisis, which violates the assumptions of inelastic demand. If demand is flexible,

[85] The law (REMIT) states that the sales offer must be based on real costs, but it is not limited to variable costs. In principle, it is therefore possible for an operator to include fixed costs in their offers. However, this would be moving into dangerous territory, where it could easily be interpreted as market manipulation. Today, there are so many demand-side and supply-side operators in the Finnish electricity market that this "one operator sets the price" scenario is not relevant, so we will leave the discussion here.

the literature has noted that an energy-only market is capable of providing sufficient electricity capacity, at least in theory. Let us examine this in more detail by delving deeper into our example.

Let's assume that in addition to electricity production, consumption is elastic. If the price of electricity is above EUR 1,000/MWh, some factories will stop production. When in our original example the gas turbines are shut down and electricity starts to run out, the price of electricity will occasionally rise to EUR 1,000/MWh, but the electricity will not run out uncontrollably. At times like these, gas turbine owners will make a profit. The gas turbines will be run at low a enough level that hours with a 1,000 €/MWh price are sufficient to cover their fixed costs. The disadvantage is that the factories cannot always operate at full capacity.



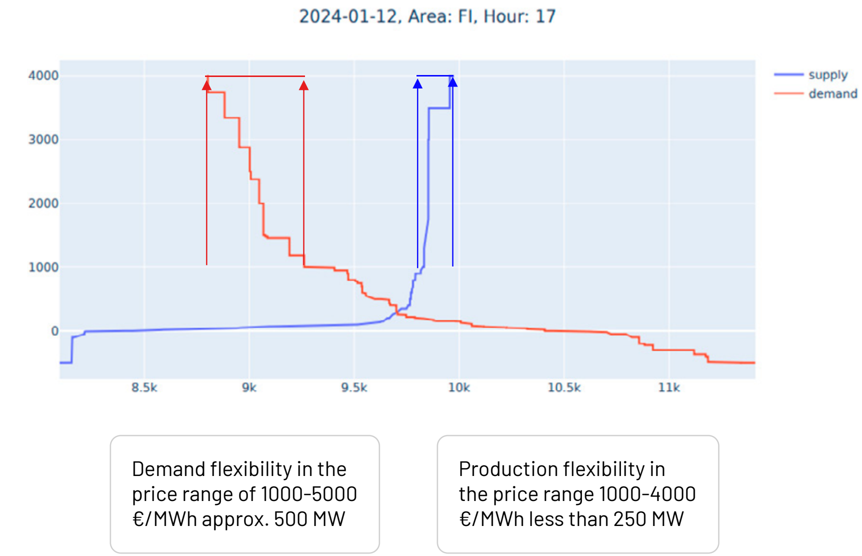


Figure 42. Demand and supply curves for 12.1.2024.

In theory, such a model is economically optimal. The model activates creativity on both the production and demand sides, so that expensive electric power plants do not have to be kept in reserve for rare consumption peaks. However, this model requires courage from political decision-makers. According to the literature, electricity prices should regularly rise very high, in rare cases even to around EUR 10 000 /MWh. In everyday discussion, demand-side flexibility often refers to a small shift in consumption from one hour to the next, which does not cause much harm to anyone. As in our example, these required extreme prices raise the ugly side of demand-side flexibility, i.e. cutting demand.

The energy crisis showed that if the price of electricity rises high for a long time, and consumers or industry start to complain, the political tolerance for it is low. The energy-only model is theoretically optimal for society. However, the model involves large price fluctuations, both quarterly and annually. If the system is repeatedly interfered with through subsidies and taxes, the system will drift further and further from the optimum. In order to achieve sufficient investments on market terms, a sufficiently high electricity price is needed. In the Nordic countries, the price of electricity is very weather-dependent. Even when there is a shortage of electricity production in an extreme situation, everything can go well for years if the weather is favourable. The price signal indicating a need for new electrical power capacity would probably emerge in a cold and dry year. After the additional need has been identified, the price of electricity might, with bad luck, remain high for several years while new capacity is built.

During price spikes, the temptation for political intervention increases. It is politically easy to punish energy producers for "unearned income". In 2023, a Windfall tax was introduced during the energy crisis, when fossil energy became scarce and the market price of electricity rose sharply. Companies that built hydropower, nuclear power and wind power were seen as benefiting undeservedly from the fact that they had built emission-free energy production. Fossil fuel-based power plants were largely exempt from the tax because their costs rose at the same time. Now that the price of electricity has fallen rapidly since the energy crisis, and wind power production, for example, is unprofitable, this has not become a problem on the political agenda.

The energy crisis also showed that if a power shortage occurs in the system, energy producers are prepared to accept generous investment subsidies. During the energy crisis, the EU changed state aid rules, which enabled rapid investment subsidies. For example, in Belgium, a four-billion-euro program is acquiring additional electricity production capacity. The 2023 auction included new gas turbine plants with a combined electrical output of around 2 000 MW and a cost of over a billion euros. In 2022, the authorities in Ireland were given a mandate to acquire 650 MW of temporary generation capacity.[86] The construction of this temporary fossil-fuelled electric power plant was given permission to waive the environmental impact assessment (Huntstown). The power shortage in Ireland came about due to the simultaneous impact of several factors. New capacity acquired in the capacity market (513 MW) remained unbuilt, demand (especially data centres) grew faster than expected, the availability of old generation facilities deteriorated rapidly and old capacity was being phased out. Locally, Dublin was highlighted as a capacity constrained area, which led to the acquisition and readiness of emergency capacity.

Because EU legislation requires that the subsidies are temporary, the subsidies had to be large enough to get the projects off the ground. For example, the total cost of the 193 MW North Wall project is around EUR 500 million over five years. If the cost of other projects is the same, this would mean an annual cost of EUR 337 million. In 2024, Ireland's electricity consumption was around 32 TWh, less than half of Finland's electricity consumption. The cost of backup power, aggregated across all electricity consumption, was therefore estimated at EUR 10.5/MWh. The transmission grid operator emphasises that it is trying not to use these backup power generators, and they are not allowed to participate in reserve markets, for example. The costs of backup power are charged in electricity transmission bills. In the first year after commissioning, the transmission grid operator gave warnings five times about a tight power situation. However, no backup power generators were started in any of these cases. Once, reserve power was activated to manage a local electricity transmission bottleneck.

If an energy company risks being fined for making investments that would prevent electricity shortages, and on the other hand, subsidies are distributed for investments in an emergency situation, it is very difficult to justify investments in electricity production as a profitable business.

[86] Temporary Emergency Generation

As a result, peak production investments involve too great risks for operators to accept. State-supported solutions to manage the risk and obtain investments have been sought through capacity market studies[87] and, most recently, through a working group study on the non-fossil flexibility support mechanism approved by the EU.[88] The capacity market is a very challenging thing to legislate. It is worth noting that in Ireland, which has been hit by an electricity shortage, a capacity market is in use. Ireland's experience[89] has shown that it is possible to spend a lot of money on introducing a capacity market without having the desired effects.

9.2 EU regulation of electrical power

The EU allows a number of ways to secure the availability of electricity in situations such as a cold and windless week. The main options are:

a. market-based solutions (e.g. scarcity pricing, demand-side flexibility and storage) and

b. capacity mechanisms (e.g. the capacity market, strategic reserve and security of supply options).

All support mechanisms must be justified by an assessment of resource security, be competitive, technology neutral, open to cross-border participants and comply with CO_2 limits. The revised electricity market regulations in 2024 clarified this framework and introduced limited derogations for existing systems.

Backup power generators owned by the transmission system operator

Power plants directly owned by Fingrid are not permitted in principle. The ownership unbundling rules of the Electricity Market Directive (2019/944) prohibit the TSO (Transmission System Operator, the grid operator) from owning or controlling production. This explains why Ireland has chosen such a hugely expensive reserve power procurement model. EU rules do not allow a more pragmatic reserve power procurement model. Fingrid is responsible for the operational balancing of the electricity system in Finland. Fingrid is allowed to acquire capacity through contracts for this purpose, for example through a strategic reserve, which is done via a competitive process from market participants (generation, demand response, storage). The strategic reserve is kept outside the market and is only used in exceptional situations.

Fingrid is not responsible for the adequacy of electricity capacity in Finland, and the company does not have a way to improve the adequacy of electricity capacity. In Finland, the Government decides the target level of security of electricity supply based on a proposal from the Energy Authority. The Energy Authority therefore decides on the amount of the reserve and acquires the capacity. The EU approved the Finnish power reserve model as compliant with state aid rules and it is valid until 2032. The rules for activating the power reserve are very strict. As stated in section 2.2.4, there is no acute power shortage, so the Energy Authority does not think acquiring a power reserve is necessary. Rolling blackouts are considered a more cost-effective way of managing power shortages.

Capacity mechanisms

At the EU level, capacity mechanisms are governed by the Electricity Market Regulation (2019/943) and the CEEAG principles of state aid regulation. According to these, the mechanism must be justified by an identified problem with adequacy, be temporary, competitive, technology-neutral and allow for cross-border participation, and comply with emission limits.

In 2024, the EU reformed the regulation of Electricity Market Design Regulation, and Directive 2024/1711 and the related Regulation 2024/1747 were

[87] Kapasiteettiratkaisuiden arviointi sähkönriittävyyden varmistamiseksi Suomessa

[88] Fossiilittoman jouston työryhmän loppuraportti

[89] Kapasiteettimarkkinan haasteet – kokemuksia Irlannista

published. The reform states that capacity mechanisms will no longer be considered measures of last resort. At the same time, it limited the maximum approval period for state aid decisions by the Commission to ten years. The key conditions were competitive procurement, openness to cross-border participation, and CO_2 emission limits (550 gCO_2/kWh and 350 $kgCO_2$/kW,v for old units after 1 July 2025).

Implementation path for the national capacity mechanism:

i. First, the power deficit in winter weeks must be demonstrated using the European Resource Adequacy Assessment (ERAA).

ii. Then, an implementation plan must be presented to remove market distortions (scarcity pricing, demand response, etc.).

iii. Next, planning of the capacity model must be carried out (centralized auction, obligation model or security of supply option).

iv. Then, participation also must be opened up to capacity from neighbouring regions.

v. Finally, the Commission's state aid approval must be sought (CEEAG 2022).

Note on fuel: New fossil diesel-powered standby power plants cannot receive capacity compensation due to the CO_2 limit (550 g/kWh). Gas turbines/OCGTs can fall below the limit, but they must also be competitively priced and there must be a framework for cross-border participation.

Scarcity pricing

Scarcity pricing is a Texas-style energy-only market, where a surcharge for scarcity hours is used to increase day-ahead price volatility. The EU allows this approach in principle, and even encourages the introduction of scarcity pricing. Regulation 2019/943 requires member states, among other things, to enable a shortage pricing function in balancing markets and to make scarcity visible in prices in general (VOLL reference). The EU also has harmonised price caps for day-ahead/intraday markets (e.g. SDAC +5000 €/MWh), which are linked to the VOLL methodology. Unlike Texas, the EU requires close cross-border market integration (market coupling, transmission capacity calculation and allocation).

9.3 Emissions from heating with electricity

In Finland, the emission factor for electricity in 2024 was 24 g/kWh. The use of electricity in Finland is therefore, on average, already almost emission-free. As with district heating, the remaining emissions from electrical power are due to cold, windless spells or, for example, malfunctions in nuclear power plants. However, when viewed on an hourly basis and with consumption-weighted use, the emission factor for ground-source systems is significantly higher.

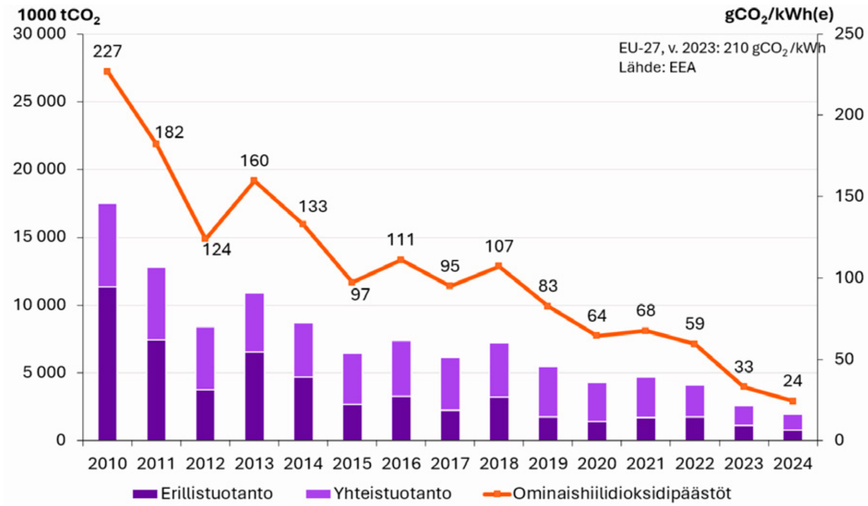


Figure 43. Emissions from electricity production.[90]
Legend from left to right: Stand-alone production, Co-generation, Electricity emission intensity

[90] Sähkötilastot - Energiateollisuus

Actual emissions

Except for the nuclear power failure in August-September, the hourly emission factor for electricity is strongly correlated with heating demand during the period under review. The emission factor for electricity is also strongly correlated with the price of electricity. When electricity is expensive, its emissions are high. Thus, when calculating the emission factor weighted by geothermal heat consumption, we arrive at a number that is 30% higher than the average emission factor for the same period. The weighted average price of electricity is also 40% higher than the unweighted average.

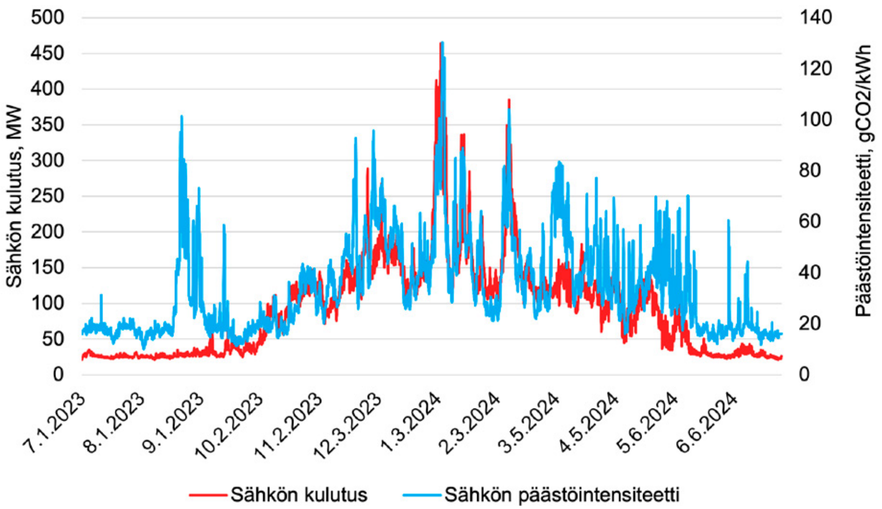


Figure 44. Electricity emission intensity and electricity consumption in the ground-source heating system in Tampere.
Legend from left to right Electricity consumption, Electricity emission intensity.

10 Acronyms

BECCS	Bio Energy Carbon Capture and Storage
BECCU	Bio Energy Carbon Capture and Utilisation
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
COP	Coefficient of Performance
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ATW	Air-to-Water (heat pump)
LULUCF	Land Use, Land Use Change and Forest
EAHP	Exhaust Air Heat Pump
SMR	Small modular nuclear reactor
TEM	Ministry of Economic Affairs and Employment of Finland *(Työ- ja elinkeinoministeriö)*
OCGT	Open-Cycle-Gas-Turbine

Report on the transition to non-combustion-based and carbon-negative district heating

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TAMPEREEN ENERGIA