REPLACING FOSSIL FUELS WITH BIOMASS IN FINLAND

Lappeenranta–Lahti University of Technology LUT

Master’s thesis

2023

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Examiners: Professor Esa Vakkilainen

Post-doctoral researcher Svetlana Proskurina

ABSTRACT

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LUT School of Energy Systems

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Keywords: biomass, bioenergy, biofuels, fossil fuels, renewable energy, energy system, carbon neutrality, carbon negativity

Biomass has long played an important role in Finland's renewable energy production. The abundance of Finnish forests has over the years made it possible to make extensive use of forests in both energy production and the forest industry. Especially in the last decade, biomass, together with other renewables, has increased its share in relation to fossil fuels to meet greenhouse gas emission reduction targets. However, the share of fossil fuels is still quite high. The EU's tightening climate measures and targets are also guiding Finnish legislation. Finland's current main goal is to be carbon neutral by 2035.

This thesis examines the role of biomass as a replacement for fossil fuels in Finnish energy production. So far, solid wood fuels have been mainly responsible for the reduction of fossil fuels. The thesis introduces biomass, its contribution in the energy system and in different energy sectors. It also reviews recent and future policies on renewable energy and bioenergy. Finally, the role of biomass in the future energy system based on renewable energy in Finland is discussed.

Biomass use is likely to increase slightly, but will stabilise in the longer term as other sustainable energy sources develop. Its use for energy production would hardly be sufficient as the only solution because of its availability, but it is an important partial solution, especially where electrification or other renewables cannot be used. The main opportunities relate to the production of biomass with a higher added value, the wider use of non-woody biomass and the combination of carbon capture and bioenergy, leading even to carbon-negative emissions.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Energiatekniikka

Janina Ramula

Fossiilisten polttoaineiden korvaaminen biomassalla Suomessa

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Biomassalla on jo pitkään ollut merkittävä rooli Suomen uusiutuvassa energiantuotannossa. Suomen metsien runsaus on mahdollistanut vuosien varrella metsien vahvan hyödyntämisen sekä energiantuotannossa että metsäteollisuudessa. Erityisesti viime vuosikymmenen aikana biomassa yhdessä muiden uusiutuvien kanssa on kasvattanut osuuttaan fossiilisiin polttoaineisiin nähden kasvihuonekaasujen päästövähennystavoitteiden saavuttamiseksi. Fossiilisten polttoaineiden osuus on kuitenkin yhä melko suuri. EU:n kiristyvät ilmastotoimet ja asetetut tavoitteet ohjaavat myös Suomen lainsäädäntöä. Suomen tämänhetkinen päätavoite on olla hiilineutraali vuoteen 2035 mennessä.

Tässä diplomityössä tarkastellaan biomassan osuutta fossiilisten polttoaineiden korvaajana Suomen energiantuotannossa. Tähän mennessä kiinteät puupolttoaineet ovat olleet päävastuussa fossiilisten polttoaineiden vähentämisessä. Työssä tutustutaan biomassaan, sen osuuteen energiajärjestelmässä sekä eri energiasektoreilla. Lisäksi tehdään katsaus viimeaikaisiin sekä tuleviin linjauksiin uusiutuvien energianlähteiden ja bioenergian osalta. Lopuksi pohditaan biomassan roolia Suomen uusiutuvaan energiaan perustuvassa tulevaisuuden energiajärjestelmässä.

Biomassan käyttö tulee todennäköisesti vielä hieman lisääntymään, mutta tasoittumaan pidemmällä aikavälillä, kun muut kestävät energianlähteet kehittyvät. Energiantuotannossa se tuskin tulisi riittämään ainoana ratkaisuna sen saatavuuden vuoksi, mutta se on tärkeä osaratkaisu erityisesti siellä, missä sähköistämistä tai muita uusiutuvia ei voida käyttää. Tärkeimmät mahdollisuudet liittyvät biomassan korkeamman jalostusarvon tuottamiseen, muiden kuin puuperäisten biomassojen laajempaan hyödyntämiseen sekä hiilidioksidin talteenoton ja bioenergian yhdistämiseen jopa hiilinegatiivisten päästöjen saavuttamiseksi.

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Janina Ramula

ABBREVIATIONS

BECCS/U	Bioenergy Carbon Capture and Storage/Utilisation
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
EFI	European Forest Institute
ETS	Emissions Trading System
FAME	Fatty Acid Methyl Esters
HVO	Hydrotreated Vegetable Oils
IEA	International Energy Agency
KAISU	Keskipitkän aikavälin ilmastopolitiikan suunnitelma/Medium-term Climate Policy Plan
Luke	Luonnonvarakeskus/Natural Resources Institute Finland
LULUCF	Land Use, Land Use Change and Forestry
MRL	Manufacturing Readiness Level
NECP	National Energy and Climate Plan
OECD	Organisation for Economic Co-operation and Development
ROBA	Robust Algae Systems
SMR	Steam Methane Reforming
TEM	Työ- ja elinkeinoministeriö/Ministry of Aconomic Affairs and Employment
TES	Total Energy Supply
TFEC	Total Final Energy Consumption
WAM	With Additional Measures
WEM	With Existing Measures

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1 Introduction

The need to replace fossil fuels with emission-free energy sources is growing rapidly as climate change progresses and climate policy requirements are getting tougher. Finland has set itself the ambitious goal of becoming the world's first carbon-neutral welfare society by 2035 (IEA Bioenergy 2021, 3). Finland has so far done well to meet the targets set in previous years and by introducing more renewable energy sources, but there is still work to be done in different energy sectors to achieve its future goals. Biomass, especially woody biomass, has carried most of the responsibility for the share of renewable energy and the replacement of fossil fuels in Finland's energy production up to this point. The purpose of this thesis is to consider the potential contribution of biomass as a replacement for fossil fuels in the energy system of Finland.

Finland is a relatively forested country compared to other countries, where woody biomass is widely used both as a raw material for forest industry and in energy production. To increase renewable energy and correspondingly reduce the use of fossil fuels, the share of biomass in different energy sectors has been increasing more or less in recent years, as in the rest of the EU, where the need for biomass is expected to even double by 2050 (Hassinen 2021). For Finland, the use of biomass has contributed to energy self-sufficiency, which is why its use has been an important part of renewable energy production. However, it has also been recognised in Finland that, despite the abundance of forests, resources are not unlimited. Therefore, the use of woody biomass needs to be considered carefully.

This thesis intends to explore the role of biomass in the current energy system and the future renewable energy-based system of carbon neutral Finland based on the latest data. The first section is an overview of the energy system in Finland and the energy sources it consists of, followed by the second section providing an introduction to biomass in Finland. The second section describes biomass as a feedstock, its production in general and its use in Finland, also discussing the sustainability aspects of biomass utilisation. Non-renewable waste will not be discussed further in this thesis. The third section takes a closer look at the current state of the energy sectors and the situation of biomass and fossil fuels in them. The fourth section covers policy actions related to renewable and bioenergy. The fifth and final section focuses on the future potential of biomass to replace fossil fuels in Finland's future energy system, using findings from other studies as a basis for reflection, which is also carried out separately for each energy sector. Finally, the strengths, weaknesses, opportunities and threats that biomass can have as a replacement are discussed through a SWOT analysis.

2 Energy system in Finland

In the early 20th century, Finland's energy was largely based on firewood from forests. Some hydropower was also built for early industrial energy needs and electricity generation. After the Second World War, the forest industry started to grow as the use of firewood started to decline. In the 1960s, the use of fossil fuels began to increase strongly, which accelerated the development of Finnish society. However, the energy crisis caused by the rise in oil prices in the 1970s led to a slowdown in the growth of fossil fuels, as more than half of energy was produced from oil at that time. Finland started to increase the share of other energy sources, for example nuclear power became part of energy production in the late 1970s. Also wood fuels started to increase their share steadily. (Statistics Finland 2007.) Figure 1 shows total energy consumption in Finland in 1970-2021.

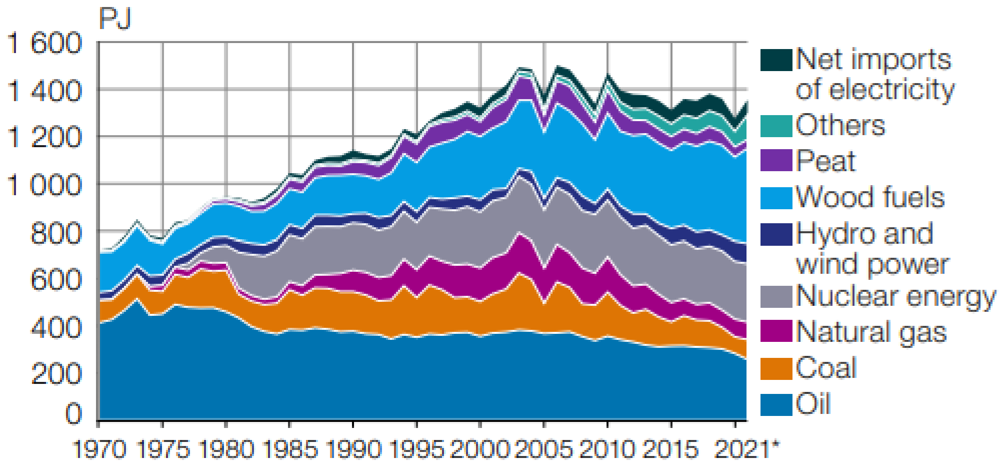

Figure 1. Total energy consumption by source in 1970-2021 (Statistics Finland 2022a, 3).

Finland's total energy consumption rose steadily up to the early 2000s. During 1970-2021, total energy consumption has almost doubled from 721 PJ to 1 356 PJ. Since the early 2000s, it has remained quite steady and slightly declining, apart from peaks downwards caused by some crises. Total energy consumption has not been increasing as the population has remained fairly stable and improvements in energy efficiency have been made. For example, Finland exceeded the EU's 2020 targets for energy efficiency by a large margin. The energy savings target for 2014-2020 was more than 85% higher than the original 49 TWh target set for Finland by EU obligations. Improvements in energy efficiency, in addition to increasing the use of renewable energy sources, have also contributed to reducing carbon dioxide emissions. They have fallen by about 34% compared to 1990 levels, although total energy consumption has not decreased at the same rate. (Statistics Finland 2022a, 3-4; IEA 2023a; TEM 2022a.)

Nowadays, Finland has a rather diverse energy mix, as can be noticed from figure 1. In 2021, total energy consumption is most reliant on wood fuels (30%), oil (19%) and nuclear power (18%). The share of nuclear power in energy production, on the other hand, increases in 2023 when the fifth nuclear power plant, Olkiluoto 3, comes into operation. Similarly, a major rise in renewables is expected in the coming years as fossil fuels are replaced to meet emission reduction targets. The use of fossil fuels has long been driven by their high energy content, storability and low cost compared to renewables. However, the cost competitiveness of renewables has improved with technological developments, political decisions and subsidies to encourage investment and deployment. Allowance prices can also be very unpredictable and may rise in the future as more stringent emission targets are set. This may lead, for example, to an increased demand for allowances or their limited supply. (Statistics Finland 2022a, 2-3; IEA 2023a; Hyppänen & al. 2022, 7, 24)

Finland aims to be a carbon neutral society by 2035. The three most energy-consuming sectors are industry, space heating and transport, respectively. Power generation in Finland is relatively low-carbon due to nuclear, bioenergy and hydropower. Renewables and biofuels accounted for 52% of electricity generation, and nuclear for 34%, whereas the rest came from fossil fuels in 2020. So almost 90% of the electricity produced was carbon dioxide-free. By comparison, renewables and biofuels accounted for 39% and nuclear for 25% of electricity generation in the EU27, with the rest coming from fossil fuels. For Finland to reach its 2035 target, more progress will need to be made in the transport and industry sectors. However, in 2021, Finland was the leader in second-generation biofuels that are produced from wood, especially biodiesel. (IEA 2023a; Statistics Finland 22, 4, 17.)

The energy system is an important part of maintaining society. Investments in the energy system consists of both public and private investments. New developments can be expected for the current Finnish energy system in terms of energy markets, energy sources, electrification, new technologies and effectiveness as the system is reformed to become more sustainable while responding to the needs of society. Therefore, the transition away from fossil fuels requires cooperation between different stakeholders and planning to achieve long-term solutions. Political decisions and legislation set the framework and conditions for action. Important factors for an energy system based on renewables are reliability, balance between supply and consumption, environmental friendliness and cost-effectiveness. The increasing share of variable renewable energy in energy production will impose additional costs on the system, especially as Finland's wind power share increases. The integration of a renewable energy system into the existing system needs upgrading and legislation to support its implementation. In addition, new innovations can create more opportunities for the energy system to achieve carbon neutrality. For example, the potential of the use of bioenergy in Finland combined with carbon capture and storage (CCS) can bring negative emissions. A diverse renewable energy system in Finland would create independence from any particular energy source, which helps the system to tolerate different types of situations and seasonal changes. This should be achieved without fossil fuels. (Hyppänen & al. 2022, 7-8, 38.)

2.1 Share of fossil fuels

Fossil fuels such as coal, oil and natural gas are non-renewable resources that have been formed by the fossilization of biomass in the Earth's crust over millions of years. The use of fossil fuels will decline in the future as resources dwindle, their prices rise and the production of greenhouse gas emissions must be drastically limited due to climate change. The goal of the 2015 Paris Agreement, to which Finland is also committed, is to limit global warming to well below 2°C, and preferably aiming for 1.5°C. To achieve this goal, strong climate actions are needed, such as limiting the use of fossil fuels. (IEA 2021, 35)

Fossil fuels have played a major role in energy systems in Finland and around the world. In Finland, the share of fossil fuels in total energy supply (TES) in 2019 was about 44% (IRENA 2022). In comparison, over 70% of energy in the EU came from fossil fuels and over 80% worldwide (United Nations 2022, 3-5). In 2021, the use of fossil fuels in total energy supply in Finland was around 38%, so progress has been made. On the other hand, COVID-19 also caused a temporary drop in the use of fossil fuels worldwide in 2020, especially oil and gas, due to travel restrictions. Despite this, in 2021 Finland's TES in terms of fossil fuels was still about 2% lower than in 2020. (IEA 2023a.)

Carbon dioxide emissions make up most of all greenhouse gas emissions. Total carbon dioxide emissions related to the Finnish energy sectors in 2020 were about just over 40

$MtCO_2$, most of which came from electricity and heat production. Transport and other industrial sectors are also the next largest producers of carbon dioxide emissions. The carbon dioxide emissions in Finland in 2020 by sector are shown in figure 2a and by fuel for the electricity and heat production sectors in Figure 2b. (IRENA 2022.)

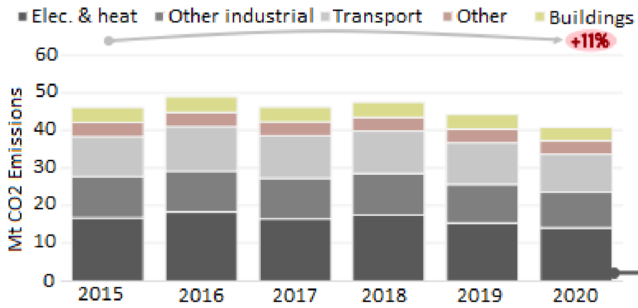

Figure 2a. Carbon dioxide emissions in 2020 by sector in Finland (IRENA 2022).

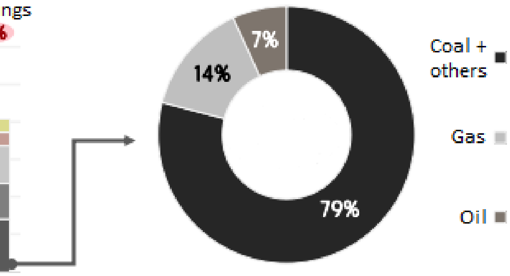

Figure 2b. Carbon dioxide emissions in 2020 by fuels in the electricity and heat production sectors (IRENA 2022).

Figure 2b shows that the majority of emissions from electricity and heat production come from coal and other sources than natural gas and oil. On average, oil and natural gas emit less greenhouse gases than coal, but are still abundant. In the early days, coal played an important role in starting the industrial revolution in Finland, which began after the mid-19th century. Coal-fired steam boilers enabled the use of machine power. Later, coal has also been used in electricity and heat production, where it still plays a role, especially in the Helsinki metropolitan area. (Hyppänen & al. 2022, 24-25.) However, Finland aims to become one of the first countries to phase out coal completely. On 1 May 2029, a law banning the use of coal as a fuel for electricity and heat production is scheduled to come into force as part of the NECP (*National Energy and Climate Plan*). By July 2022, 31 countries had set specific targets for coal phase-out in their national plans, most of them being European countries. By August 2022, Belgium, Austria, Sweden and Portugal had already phased out the use of coal in their energy production. The Finnish Ministry of Economic Affairs and Employment (TEM) has set incentives for Finnish energy companies that are phase out coal by 2025: companies receive funding for the investment costs needed for replacing coal with other energy sources. Coal would be the first fossil fuel to be phased out of the Finnish energy mix. (TEM 2019; IEA 2023a; IEA 2023c.)

Finland is not known to have any fossil fuels of its own, so they are imported. It is estimated that almost half of the coal has been imported from Russia, with the rest coming from other countries such as Poland, Colombia, Indonesia, Australia and the United States. In 2021, about 1.05 Mt of coal was imported from Russia and 1.36 Mt from other countries. The better quality coal imported from Australia and the United States goes mainly into the steel industry. Crude oil and natural gas have also been imported in large quantities from Russia in the past. In 2021, about 1 878 million m^3 of natural gas, about three quarters of the total, was imported from Russia and the remaining about 629 million m^3 from elsewhere. Oil and petroleum products were imported from Russia in the same year about 8.85 Mt which is about two thirds, and from elsewhere about 4.97 Mt, mainly from Sweden and Norway. Figure 3a shows 2021 coal and oil imports by country and figure 3b shows correspondingly natural gas imports. (Hiilitieto ry 2023; Statistics Finland 2022a, 49.)

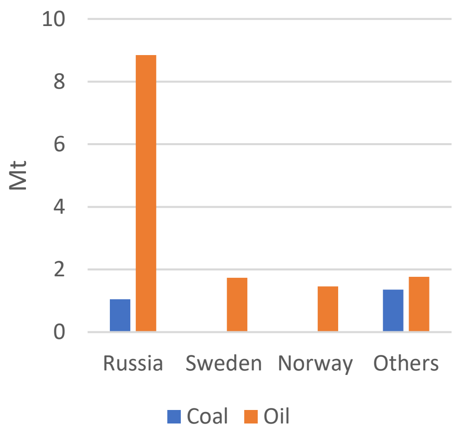

Figure 3a. Coal and oil imports by country 2021 (Statistics Finland 2022a, 49).

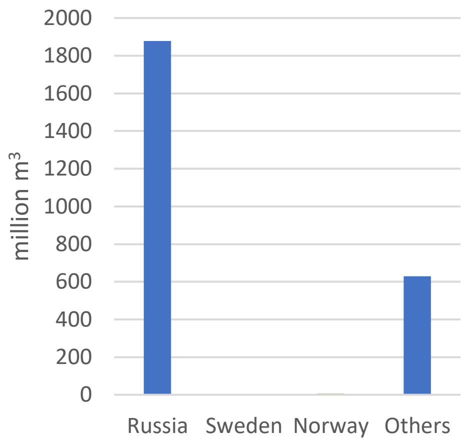

Figure 3b. Natural gas imports by country 2021 (Statistics Finland 2022a, 49).

Figures 3a and 3b show that up until 2021, Russia has played the most important role in importing fossil resources to Finland. However, coal imports from Russia have fallen considerably since the war in Ukraine and due to the green transition. The same applies to crude oil and natural gas imports, which were also reduced due to the sanctions imposed by the war. Imports of crude oil have therefore been mostly replaced by increasing imports from Norway and imports of natural gas have been replaced by increasing imports from countries such as Estonia and also Norway. As with coal, the aim is also to reduce their use in order to meet climate targets. (Statistics Finland 2022a, 49; Penttilä 2023; IEA 2023b, 161, 172.)

2.2 Biomass as part of renewable energy

Biomass is organic matter of plant or animal origin that can be used as a source of energy. Energy produced from biomass is considered renewable energy because it renews at a relatively fast rate. For this reason, peat, which is also derived from organic matter, is not classified as renewable energy because of the slowness of its formation. Biofuels can be produced from biomass by conversion process for energy production and they can be in gas, liquid or solid form. Examples of these are biogas, bioethanol and wood pellets. Biofuels have the potential to replace fossil fuels as energy sources. (Poulopoulos & Inglezakis 2016.)

The share of renewable energy in total energy consumption was 42% in 2021, as can be seen in figure 4, which shows the percentages of the different energy sources presented earlier in figure 1. Figure 5 in turn shows in more detail the energy sources from which renewable energy is produced.

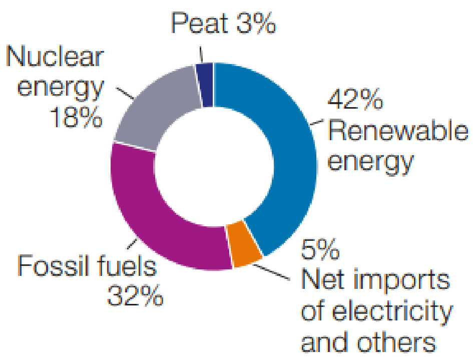

Figure 4. Total energy consumption in 2021 (Statistics Finland 2022a, 12).

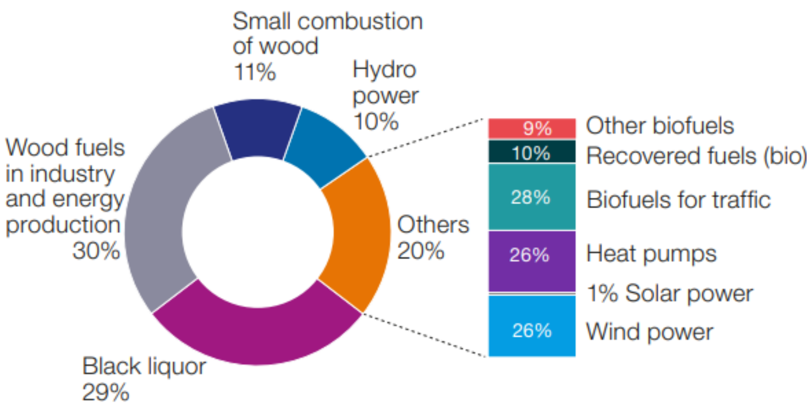

Figure 5. Renewable energy share in total energy consumption in 2021 (Statistics Finland 2022a, 11).

Renewable energy sources in Finland include wood fuels for industry and energy production, black liquor, small combustion wood, hydropower and others. Broadly estimated, more than a third of total energy consumption would therefore come from bioenergy alone. In electricity generation hydro and wind power compete with bioenergy for shares of renewable energy, but in the heating sector, bioenergy has a major share of renewable energy sources. For example, 44% of the whole district heat production was from wood residues and chips in 2020. In fact, the heating and cooling sector has the highest share of renewables compared to other sectors, which was 58%. In the gross electricity consumption sector 40% was from renewables and in the transport sector 13%. At EU level, the corresponding shares of renewables for the heating and cooling sector were only 23%, for gross electricity consumption 37% and for transport 10%. In other sectors, Finland is at about the same level as the EU, but bioenergy is largely responsible for Finland's lead over the EU in renewable energy use in the heating and cooling sector. (Statistics Finland 2022a, 9-12, 37; IRENA 2022.)

In 2020, a comparison was made between the EU27 countries on the achievement of their renewable targets. The EU target was 20%, which was a bit exceeded. Sweden, Latvia and Finland had the most ambitious targets with 38%, 40% and 49% respectively. France missed its target 23% most clearly and the share of renewable energy remained below 20%. Sweden, on the other hand, was the only EU country ahead of Finland in renewable energy share, reaching 60%. Similar to Finland, bioenergy use in Sweden accounts for a large share of renewable energy. Especially in the heating sector, bioenergy has helped both Finland and Sweden to make the transition towards lower emissions. (Statistics Finland 2022a, 9-10; IEA Bioenergy 2021a, 19-20.)

3 Biomass in Finland

One of the special features of Finland is its high availability of biomass resources, which are mainly forest. By far the most commonly used biomass type is solid biomass as in the rest of the world. Other types of biomasses, such as liquid biofuels, biogas and renewable waste, are also increasing their shares, but are still relatively minor compared to solid biomass. Finland is the second most forested region in the EU, with around 22.5 million hectares in 2020. This is about 75% of Finland's total land area. Only Sweden had more forested areas, with around 26.5 million hectares. Figure 6 shows the distribution of forest areas in the EU27. (Hyppönen & al. 2022, 10; IEA Bioenergy 2021a, 10; EEA 2023; IEA Bioenergy 2021b, 2.)

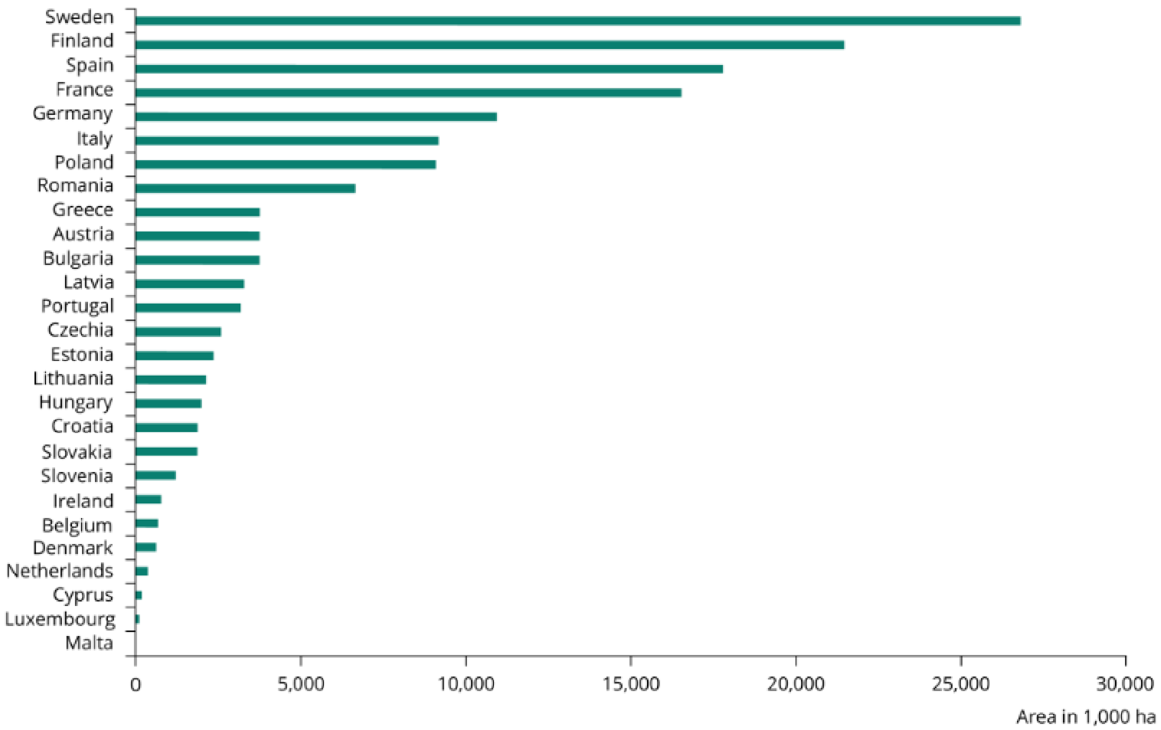

Figure 6. Forest area in the EU27 in 2020 (EEA 2023).

It can be noticed that forested areas are not evenly distributed among the member countries. Around two-thirds of the total forest area in the EU belonged to the six largest holders. In the EU, the cause of decreasing forest area has mainly been due to urbanisation and deforestation for agricultural land. Thus, in many places, biomass availability may be quite limited, and the use of biomass has to rely on imports. In Denmark, for example, forest area is relatively small compared to its supply. (IEA Bioenergy 2021a, 10-11; EEA 2023.)

The per capita supply of bioenergy in Finland in 2019 was around 70 GJ/capita, which was the highest in the world. The corresponding number in Sweden was about 50 GJ/capita and most other countries were in the range of 8-15 GJ/capita. Although solid biofuel use in Finland is high per capita, solid biofuel use per forest area is still low, roughly one tonne of dry woody biomass per hectare. This is mainly due to Finland's low population density, strong forest industry and the relatively large area of forests. (IEA Bioenergy 2021a, 10; IEA Bioenergy 2021b, 7.) Especially in recent times, Finland has focused on sustainable forest management, which aims to ensure the thriving of forests for generations to come. Forest management is ensured through certified nationally and internationally agreed practices. In addition to this, natural resource planning, spatial ecological planning, legislation and various types of guidelines are also used to manage forests. (Metsähallitus 2023.)

The largest forest biomass potentials are naturally in countries where wood is used as fuelwood and there is also potential for residues from harvesting stemwood. Besides Finland, these countries include Sweden, Germany, France, Poland and Spain. In some countries, however, there is considerable potential for residual wood, despite less harvesting of stemwood. Forest residues are then obtained from thinnings. Countries with this kind of potential are Bulgaria, Italy, Slovenia and Slovakia. (Panoutsou & Maniatis 2021, 48.)

Biomass can also be produced from non-forest raw materials, such as from agriculture and biowaste. The most exploited biomass potential from agriculture in the EU is straw, the main source of which is cereals. Straw can also be produced from grain maize stovers and rapeseed or sunflower stubbles, among other things. France, Germany and Italy, for example, have one of the highest potentials for agricultural biomass in the EU. The availability of biomass from biowaste is more challenging than from other sources, as biowaste is collected not only from households but also as part of municipal solid waste. The composition of biowaste is also very heterogeneous and may contain impurities that hinder its use as a fuel. Nevertheless, biowaste has potential for bioenergy production. The potential of biowaste is often correlated with population size or economy, but there are also countries where the potential is higher than expected for these parameters. In these countries, such as Denmark, Austria and Belgium, waste recovery rates are high. In Finland, the potential of forest biomass is so great that biomass from agriculture and biowaste has not yet played a significant role. (Panoutsou & Maniatis 2021, 47-49.)

3.1 Biomass feedstocks

Biomass feedstocks can be used to produce heat, electricity, biofuels and bioproducts. Feedstocks can be divided into four types, which are primary, secondary and tertiary residues and energy crops. Primary residues are biomass sources that are directly harvested from raw matter, such as residues from thinning and harvesting. Secondary residues are the raw material collected from the processing of primary biomass residues, such as sawdust, bark and oil seed meal. Tertiary residues come from end-use consumption such as food and material waste. Energy crops are biomass sources that are directly cultivated for energy production. Figure 7 shows the energy crop and primary, secondary and tertiary residual flows to energy consumption. (Van Stralen & al. 2016, 20-21.)

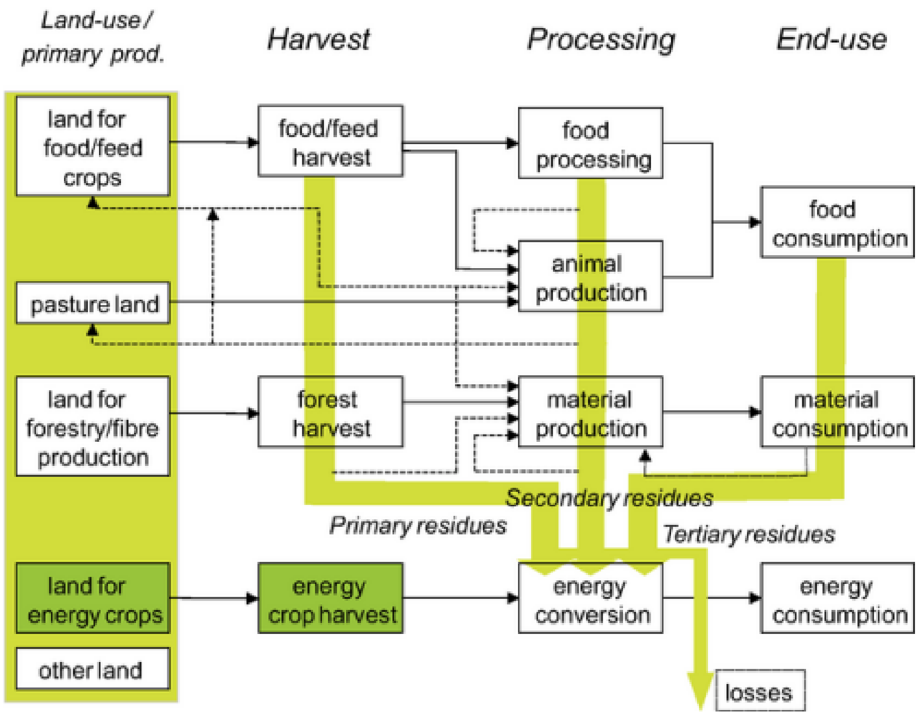

Figure 7. Flows of biomass feedstocks (Van Stralen & al. 2016, 20).

The feedstocks that are mainly used to produce biofuels for bioenergy production can be divided into the following categories: agricultural residues, forestry residues, energy crops, algaes and wastes containing biomass. (Van Stralen & al. 2016, 20.)

Agricultural residues are raw materials typically derived from harvesting or crop processing. Most optimally, agricultural residues are not raw materials which are used as food, feed or agricultural products, but recovered from the remains of their production. For example, cereal straw can be used for animal feed and bedding, in addition to energy production. However, there is great potential for the use of agricultural residues as a biofuel feedstock not to compete with land for food or feed production and forestry. Examples of agricultural by-products that could be used as feedstock for biofuels include straw, the non-edible parts of maize, such as stalks, leaves, husks and cobs, bagasse and other agricultural processing waste, like meat and bone meal. In Finland, as well as in other EU countries, straw is the most typical form of agricultural residue used. (Panoutsou & Maniatis 2021, 42, 47; Poulopolulos & Inglezakis 2016.)

Forestry residues are the most common biomass feedstock in Finland. This is due to high volumes of fuelwood and harvesting of stemwood, which yields high amounts of forestry residues. Finnish forests do not grow energy wood separately. Wood used for energy production is typically residues from the forest industry and harvesting. Typical forestry residues used in energy production are sawdust, bark, wood chips and other residues from harvesting and forestry processes. The by-products of harvesting are tree tops, branches and other cuttings that cannot be used in the wood or pulp industry. For example, the by-product of pulp boiling is black liquor, which is also widely used in Finnish energy production, as can be seen from figure 5 in the previous chapter. (Panoutsou & Maniatis 2021, 48; Hyppönen & al. 2022, 26.)

Energy crops, also known as dedicated crops, are biomass cultivated directly for energy production. They have fast growth rates and can be converted into solid, liquid or gaseous biofuels. Examples of energy crops cultivated on land include switchgrass, miscanthus, sugar cane, sorghum and different oilseeds. Examples of woody energy crops with a longer growth period include poplar and willow. Typical energy crops grown on land in Finland include reed canary grass, willow and rapeseed. In Finland, however, the use of energy crops has been rather limited and mainly used in larger power plants. (IIASA 2012, 234; Motiva 2020a.)

Algae are biomass grown in fresh water or in the ocean and they can be divided into microalgae and macroalgae. Microalgae are microscopic unicellular algae that can be found in both fresh and salt water. Macroalgae, also called seaweeds, are larger algae typically found in marine waters, but can also be found in freshwater. Microalgae grow faster than macroalgae and contain more oil, but macroalgae are easier to harvest and simpler to grow. For example, algae can be used to produce biodiesel, bioethanol and biomethane. The problem with both algae is still that the current technology is not yet mature enough to be economically viable and they are treated in a different way than conventional biomasses. However, algae are efficient at converting sunlight into biomass, which is why the development of related technologies will continue. In Finland, there is currently barely no biomass production from algae, but studies are ongoing. (IIASA 2012, 234; SYKE 2016, 21, 26, 40.)

In principle, biowaste includes different biomass containing waste streams, such as wood-based waste, animal waste, agricultural waste, industrial waste, municipal solid waste, sludge and sewage, among other things. The EU Circular Economy Package has set a target in 2020 that 55% of municipal solid waste should be recycled by 2025, 60% by 2030 and 65% by 2035. However, the recycling rate of solid municipal waste in Finland has remained around 40% for several years and the amount of municipal waste has been on the rise. Finland does not seem to meet the 2025 target. In particular, the collection and recycling of biowaste and plastics needs to be improved. In 2021, the Finnish Government adopted a decision on a strategic programme for the circular economy, which aims to create a new economic foundation based on the circular economy by 2035. (Panoutsou & Maniatis 2021, 44; YM 2023a; YM 2023b.)

3.2 Biofuel production in general

Biomass feedstocks can be refined into more valuable biofuel products. Different feedstocks have their own production, harvesting, storage, handling and processing methods. The biomass supply chain essentially involves harvesting and collection of raw material, transportation, pre-treatment, refining and storage, culminating in the energy end-use. Figure 8 below illustrates the main activities in the biomass supply chain. (WBA 2018, 1; Atashbar & al. 2017, 7.)

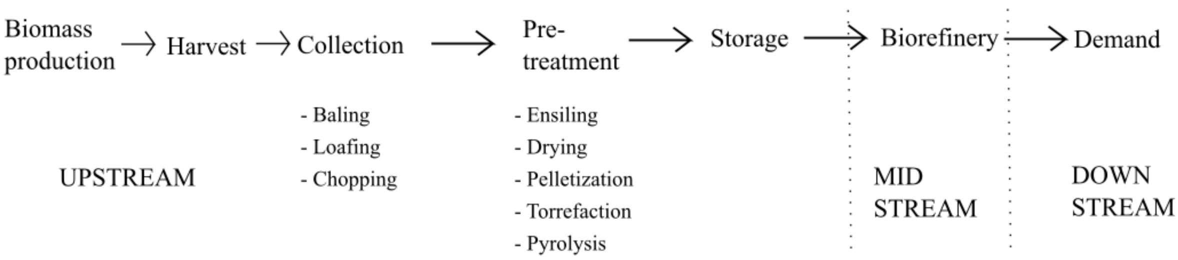

Figure 8. The main activities in the biomass supply chain (adapted Atashbar & al. 2017, 7).

The main activities are divided into three segments, such as upstream, midstream and downstream, like in figure 8. The upstream represents the preliminary stages before refinery. After harvesting, raw materials can be assembled into a form that is easier to collect, for example straw is baled or chopped to fit into a smaller transport and storing space. Forest feedstocks, in turn, can be chipped on site by roadside chipping or transported to a terminal for chipping. In addition, there are other ways to collect agricultural and forestry raw materials, such as the exploitation of agricultural and forestry by-products. Biowaste and algae also have their own different ways of harvesting. It is also worth noting that biomass harvesting is the most impacting stage in terms of environment and economic costs. (Atashbar & al. 2017, 5-7; WBA 2018, 2-3.)

Often, biomass is stored between different stages of the supply chain. Especially in electricity and heat production, energy demand varies seasonally. Therefore, the duration of storage can be shorter or longer. Storages act as buffers for future needs and aim to prevent the loss of dry matter. For example, the harvesting season for energy crops is relatively short, making storage solutions important. Depending on the quality of the biomass and local weather conditions, biomass can be stored in the open air, under shelters or in centralised storage facilities, possibly including fans for ventilation. If necessary, intermediate storage between harvesting and the production plant can be combined with pre-treatment of the biomass, so that the material requires less space and is cheaper for further transportation. (WBA 2018, 4-5; Atashbar & al. 2017, 7.)

Biomass pre-treatment prepares the feedstock for a more exploitable and valuable form for biofuel production in biorefineries. Typical pre-treatment methods include mechanical, biological, chemical and thermo-chemical conversion. These processes involve, for example, biomass drying, densification, torrefaction and pyrolysis. Biorefineries, in turn, combine several different conversion stages to produce end products. Figure 9 below illustrates the processing steps of the conversion processes in a biorefinery into end products. (WBA 2018, 4; Ubando & al. 2020, 5.)

Mechanical conversion can be used to produce pellets to fuel electricity and heat production plants, among other things. Straw, for example, has low energy density and requires plenty of storage space, so compressing straw into pellets or briquettes can be useful. (Ubando & al. 2020, 5; Motiva 2020a.)

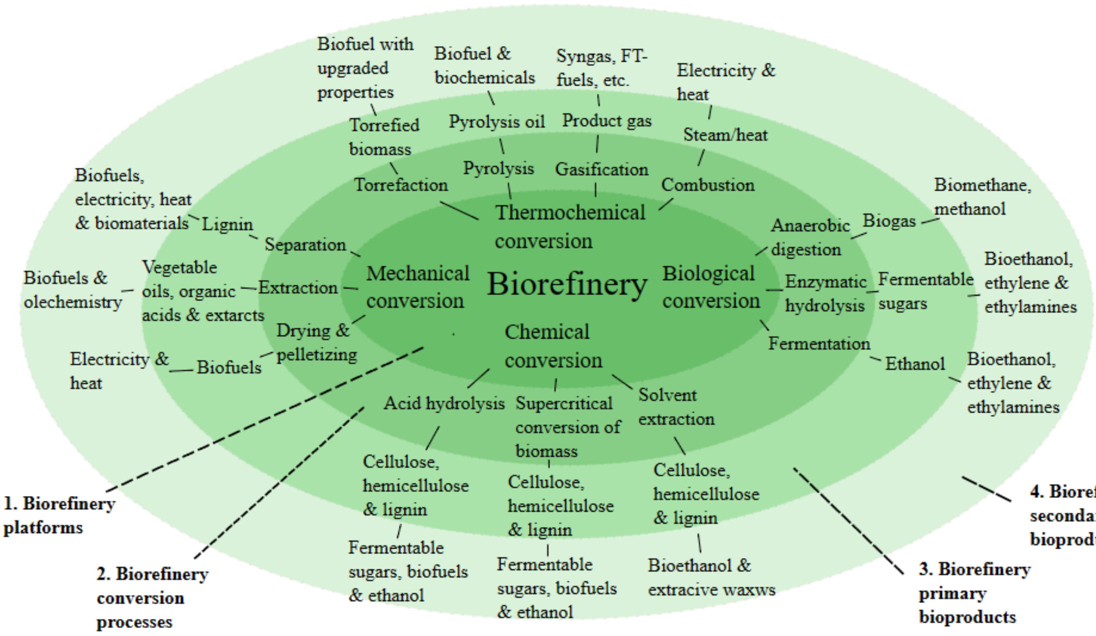

Figure 9. Steps in the conversion process of a biorefinery to end products (adapted Ubando & al. 2020, 5).

Thermochemical conversion can be used, for example, to torrefy, pyrolyse or gasify biomass. In pyrolysis, biomass undergoes thermal decomposition at increased temperature without oxygen. The products of pyrolysis include bio-oil, biochar and syngas. Bio-oil and syngas can in turn be further processed into fuels such as biodiesel, ethanol and methanol. Torrefaction is a special case of pyrolysis, where the residence time is shorter and the temperature is milder, so the biomass decomposition is not as extensive. Torrefaction aims to convert biomass into more carbon-rich biocoal by removing moisture and volatiles. Torrefaction combined with pelletizing or briquetting provides a high energy content fuel that requires less space both in storage and in transport. In gasification, biomass is converted to a gaseous state at higher temperatures and with controlled supplies of oxygen. The end product is a product gas, such as syngas. (Ubando & al. 2020, 5; IEA 2017, 37.)

Chemical conversion involves various conversion methods based on chemical reactions. Solvent extraction, acid hydrolysis and supercritical conversion of biomass can be used, for example, to produce ethanol and other biofuels from cellulosic feedstocks. Biological conversion, in turn, is based on favourable changes in biomass caused by biological reactions. These conversion processes include biomass digestion under anoxic conditions, fermentation and enzymatic hydrolysis. The end products are such as biomethane and bioethanol. Anaerobic digestion of biowaste for biogas production also helps reduce greenhouse gas emissions, especially methane. (Ubando & al. 2020, 5; IEA 2017, 50.)

In addition to the conversion methods, biofuels can be classified into four categories by generation, representing the level of advancement of biotechnological processes. First generation biofuels are based on edible biomass, such as vegetable oils, sugars and animal fats, for which most conversion sites are designed. The main products are biodiesel, ethanol and gas. Second generation biofuels are not produced from edible biomass sources, but from crop and forestry residues and industrial waste. Typical second generation biofuel feedstocks include straw, stovers and dedicated non-edible crops. The third generation includes aquatic organisms, such as algae, and the fourth generation is made up of various synthetic biofuels and also biohydrogen, which are in their preliminary stages. The fourth generation also includes carbon capture technologies to convert carbon dioxide into biofuel. (Atashbar & al. 2017, 4; Poulopolulos & Inglezakis 2016.)

In addition to the above, the biomass supply chain includes transport between facilities for biomass and biofuels. The choice of transport mode depends on the type of biomass, the stage of the supply chain, the distance to be transported, geographical conditions and infrastructure. Trucks and other road vehicles are the most common mode and the best for short distances, around a few hundred kilometers. Its advantages are the flexibility to collect and deliver to different locations, but the increased costs over longer distances may make it unprofitable. It is often more cost-effective and less polluting to make these transports by train. Ships and other waterway transportation, on the other hand, are the most profitable means of transporting large loads. Over long distances, emissions per kilometers are only a tenth of road transport. Biogas and bio-oil can be transported efficiently in pipelines, but the cost of new systems are high and is only suitable for certain types of biomass. Biomass can also be transported by a combination of the above modes of transport, depending on the situation. For example, long-distance transport will become more important in many European countries that do not have enough domestic biomass to meet their needs. (WBA 2018, 5, 8.)

3.3 Hydrogen production from biomass

Hydrogen may play an important role in the future as an energy carrier, and it is also an important industrial raw material. Electrification can be challenging in sectors such as heavy transport, chemicals and metals. Around 96% of the hydrogen used in Finland is produced from fossil fuels. Thus, using hydrogen would help to reduce carbon dioxide emissions significantly. (Hyppönen & al. 2022, 30.) Hydrogen production processes can be divided into thermochemical, electrochemical and biological processes. In part of the processes, hydrogen can be produced from biomass or as a by-product of biomass processing. (Prabhansu & al. 2022, 399.)

SMR (*Steam Methane Reforming*) is a very commonly used method to produce hydrogen from natural gas, which is currently used to produce the majority of Finland's hydrogen. A similar technology can also be used to produce hydrogen by reforming biomass fuels, replacing natural gas with liquid biofuels such as cellulosic ethanol or bio-oils. The reforming reaction with steam occurs only at higher temperatures, typically above 700 ℃. (Hyppönen & al. 2022, 31; Prabhansu & al. 2022, 400-401.)

In the biomass gasification process, carbonaceous material is transformed at high temperatures, typically 700 ℃-1000 ℃, in the presence of oxygen or steam into carbon monoxide, hydrogen, carbon dioxide and other species. The process happens without combustion. Absorbers or special membranes can be used for hydrogen separation. (Prabhansu & al. 2022, 400-401.)

In biomass pyrolysis, biomass is carbonised, which involves heating it under anoxic conditions. This produces condensed liquids, solid carbon and gases such as hydrogen, which can be extracted. (VTT 2016, 16.)

The biological process also has the potential to produce hydrogen through biological reactions from microbes using sunlight or organic matter. However, the biological processes are still at an early stage of development, as the hydrogen yield in the reaction is low. The potential for sustainable hydrogen production is nevertheless very high. (Prabhansu & al. 2022, 402.)

Hydrogen production by thermochemical water splitting does not directly utilise biomass, but it can utilise the heat produced by biomass combustion. Splitting occurs at high temperatures of 500 ℃-2000 ℃. However, centralised solar energy or industrial waste heat, for example, may be more favourable options. More consideration has been given in Finland to electrolysis of water using electricity. Hydrogen could be used as a storage for variable renewable electricity generation, thus balancing production. Although hydrogen produced from renewable sources consumes a lot of electricity, its production by electrolysis is emission-free. (Prabhansu & al. 2022, 401-402.)

Hydrogen has a high energy density and can be used as a seasonal storage. It has various applications in transport, heat and power generation and industrial sectors. However, hydrogen technology still needs technological development to become widely viable. The main challenges for hydrogen are related to its transport, storage, production costs and safety considerations.

3.4 Biomass use in Finland

Wood consumption in Finland has almost doubled in the last 60 years, and in that time the annual growth of forests has more than doubled. Around 90% of Finland's bioenergy is produced from wood-based biofuels. Most wood is used in the forest and energy industries. The main wood fuels are wood chips, bark, sawdust, forest residues, recycled wood and waste sludge from pulp mills, like black liquor. In 2021, the use of roundwood in Finland was about 85.1 million m^3, which was 9% more than in the previous year and represents the highest volume in history. About 72.2 million m^3 was consumed in the forest industry, of which imports accounted for 14%. The rest, about 6.5 million m^3 was used for energy purposes as firewood for small houses and 6.4 million m^3 was used as energy wood for heating and power plants. This means a total of 12.9 million m^3 for energy production, which was about 14% more than in the previous year. About 27.5 million m^3 of forest industry by-products and wood residues were recovered, of which 64% was used in energy production and the remaining is used to produce bioproducts. The forest industry is striving to produce more high-value products. The new forest industry plants are biorefineries that utilises different technologies. For example, in the Finnish pulp industry, commercially mature technologies include burning bark and its gasification, biogas production from sludge, ethanol production and lignin separation from black liquor in sulphite pulp mills and refining of pine oil for transport fuel. (Bioenergia ry 2023; Luke 2022; Hyppönen & al. 2022, 47.)

Figure 10 shows a map of bioenergy producers in Finland 2022, produced with the Finnish Bioenergy Association in co-operation, excluding sites using 100% forest industry by-products (Bioenergia ry 2022).

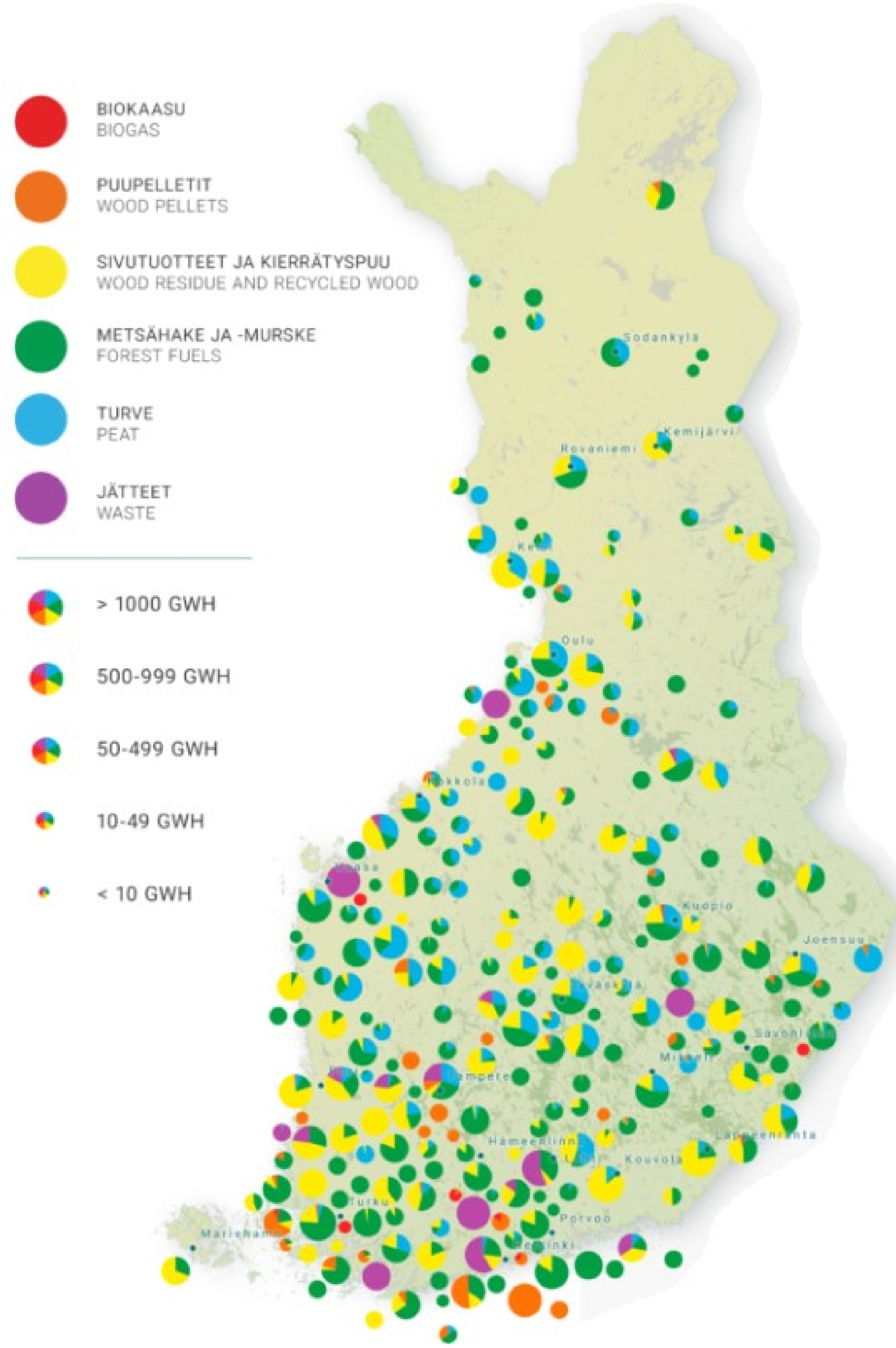

Figure 10. Bioenergy producers in Finland in 2022 (Bioenergia ry 2022).

The majority of bioenergy producers use forest fuels, wood residues and recycled wood in their energy production. Wood pellets are used to some extent mainly in southern Finland and biogas in a few small plants around the country. Peat was used in many agglomerations and industrial plants for heat and power generation in central and northern Finland. However, demand for peat in energy production has fallen rapidly, leading to a decline in peat production in recent years. Waste was incinerated in a few larger plants. Finland's waste incineration potential is nearly fully exploited, when considering the EU targets for recycling. (Bioenergia ry 2022; Bioenergia ry 2023; Hyppönen & al. 2022, 29.)

About 1 TWh of biogas was produced in 2021. Most of the biogas was produced from biowaste and sewage sludge. Half of this was used for heat and electricity production and about 15% for road transport. The share of biomethane produced in 2021 was around 20% of the biogas produced. Biomethane is purified from biogas and it was mainly used for road transport. The potential for the production of biogas from waste materials is estimated to be 11 TWh annually. In 2021, Finland had 33 landfill gas collection sites and 79 biogas production reactor plants. Biogas production is expected to grow in the coming years. (Suomen Biokierto ja Biokaasu ry 2023; Hyppönen & al. 2022, 29.)

About 1.1 TWh of bioethanol was used in Finland in 2020. It is for example produced by fermenting waste containing sugars, starch and cellulose. Technologies have been developed in Finland to produce bioethanol from biomass, the food industry and municipal waste. Bioethanol can be used in low quantities mixed with fossil petrol. Biodiesel production in 2020 was around 3.5 TWh. It can be made from fatty or oily waste or, as in Finland, from pine oil, a forestry by-product. (Hyppönen & al. 2022, 29; Motiva 2020b.)

In Finland, there are an estimated 30 000 detached houses and larger facilities that use pellets as fuel. The raw material for wood pellets in Finland is typically forest industry by-products and residues, such as sawdust, cutter chips and other bark-free materials. There are about 20 operating pellet plants in Finland. In 2022, Finland produced 360 000 tonnes of wood pellets, 2% less than in the previous year. A total of 187 000 tonnes of pellets were imported into Finland, most of which came from Russia, 73 000 tonnes. The previous year, 196 000 tonnes were imported from Russia. However, imports from other countries have increased to compensate for reduced imports from Russia. Exports from Finland increased by a third to 18 000 tonnes, most of which to Denmark and the United Kingdom. Thus, taking into account domestic production as well as imports and exports, domestic consumption of pellets was 529 000 tonnes, 4% less than in the previous year. The vast majority of pellet consumption is in heating and power plants and the rest in households and agriculture. Figure

11 shows the production, exports and imports of wood pellets from 2008 to 2022. (Bioenergia ry 2023; Luke 2023a; Luke 2023b.)

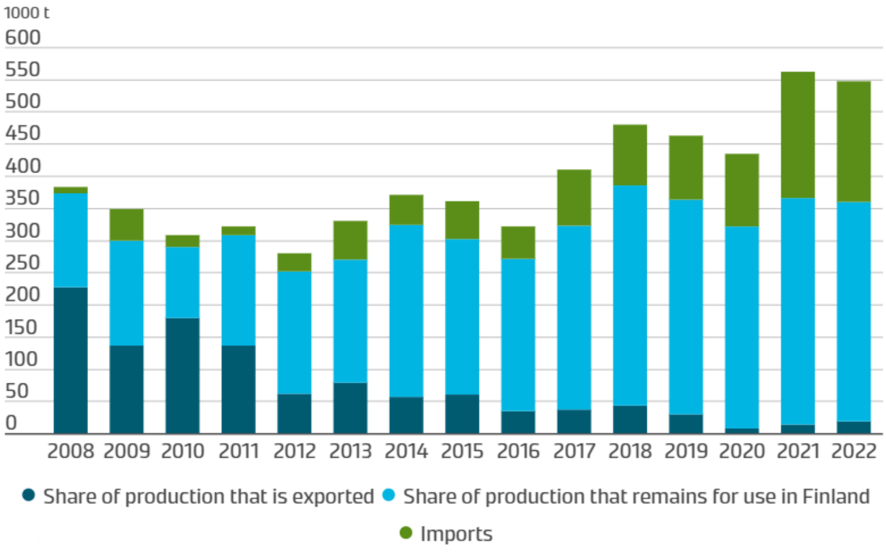

Figure 11. Wood pellet production, exports and imports 2008-2022 (Luke 2023b).

Wood pellet production is not as high as in other European countries such as Germany and Sweden, despite the availability of wood raw material. The reasons for this include strong competition for the raw materials used to produce wood pellets, which are also used as fuel in heating and power plants. The low cost of other solid biofuels, like wood chips, has made challenges for wood pellets in cost-competitiveness. In addition, cheap pellets imported from Russia in the past have made domestic production less attractive. The production of wood pellets is also linked to the production volumes of the forest industry, due to the by-products and waste wood from the forest industry. The war in Ukraine caused a reduction in imports of wood material and pellets, leading to more demand in the domestic market and other countries. Trade in wood biomass and pellets has become increasingly important, especially in Europe. Increasing the production of pellets in Finland could be attractive both for meeting domestic consumption and for export. The competitiveness of wood pellets could also be helped by increasing subsidies. (Luke 2023b; Tuohiniitty 2022.)

3.5 Sustainable development aspects of biomass utilisation

It is crucial to consider the technical, economic, environmental and social aspects of biofuels, as their demand is likely to grow as the use of bioenergy increases to help meet climate targets. The Finnish energy and climate strategy aims to increase significantly in particular the use of forest chips, biofuels for transport and wind power (Motiva 2020b). Increasing biomass consumption may also lead to increasing imports, in which case the sustainability of the origin of the imported biomass needs to be considered. Most of the domestically produced biomass comes from forests, as discussed in previous chapters, which means that the sustainability aspects of Finnish forest industry is an important issue. The sustainability of biomass for biofuels needs to be assessed from different aspects, as required by the EU's RED sustainability criterion. (European Commission 2023a.)

3.5.1 Technical aspect

The technical aspect involves contributing to sustainable development through technical solutions. One of the main ones is resource efficiency. The conversion process of biomass to biofuel at different stages should be carried out as efficiently as possible using more efficient technologies, such as advanced combustion systems and biomass conversion methods. New technologies can also be able use broader feedstock base, which improves the availability of raw materials. This allows previously unprofitable biomass feedstocks to be exploited, which would result in less waste and carbon dioxide emission from biomass. In addition, technological research and development is essential to develop new technologies to produce better quality biofuels and products in biorefineries. MRL (*Manufacturing Readiness Level*) is used to assess the maturity of a technology, which is measured by the availability of the technology on the market. Also worth noting is the need for sustainable infrastructure to energy and auxiliaries supply, like pipelines for gas and hydrogen, whether it is already built or needs to be renovated or built from scratch. It would be best to take advantage of the infrastructure that is already existing. The biomass supply chain should also be optimised by minimising transport distances and aiming to integrate processing steps. The standardisation of biomass also facilitates their use in conversion processes, which reduces operational challenges. Technological solutions can reduce emissions, for example through filters or flue gas treatment, or even remove carbon dioxide from the atmosphere through carbon capture technology. Finnish companies have strong expertise in bioenergy technologies and their development. (Thrän & al. 2020, 4, 6; Hyppönen & al. 2022, 48; Motiva 2020b.)

3.5.2 Economic aspect

The economic aspect of biofuels relates to the profitability and reliability of biomass use. The cost of using biofuels must be competitive with fossil fuels. Although Finland has abundant forests, these resources are also limited. Finland has so far relied heavily on imports from Russia, but to meet its own needs it will have to increase imports from elsewhere. As the need for biomass increases, the importance of sustainable biomass trade grows. Therefore, it is necessary to pay attention also to the sustainability of the origin of biomass, which the EU, for example, is trying to manage through sustainability criteria. In Finland, however, most of its wood demand is met domestically. The majority of Finnish forests are in private ownership. The use of forest resources must be based on sustainable and over generational use, so that forest resources will be at least as abundant in the future as today. Domestic biofuel production and refining leads to add not only biofuel quality but also its economic value. Domestic biomass processing also has a positive impact on the local economy, for example through job creation. (Luke 2022; Metsähallitus 2023; Thrän & al. 2020 4-5.) Finland's Bioeconomy Strategy, published in 2014, aims to increase the output of the bioeconomy to €100 billion by 2025 and create 100 000 new jobs. By creating sustainable business models in the long term creates a favourable economic basis for the development of biomass use. (IEA Bioenergy 2021b, 15.)

3.5.3 Environmental aspect

Finland is the most forested country in Europe in terms of per capita. In 2022, the total removal of trees was around 90 million m^3, which includes about 14 million m^3 of dead wood remaining in the forest. This was 2% less than the previous year. About 96% of the harvesting potential in Finland was harvested and exceeded by 3-6% in six municipalities. Recently, the large volume of forests being felled has become a topic of discussion. It has been discussed that net emissions from the land use sector create uncertainty for achieving Finland's ambitious 2035 carbon neutrality target. The OECD's 2021 analysis has assessed that the demand for biomass in the roadmaps would be too high to match the 2023 targets. Therefore, in its 2023 Finland Energy Policy Review, the IEA has advised the Finnish government to make clarified quantitative estimate of the amount of logging allowed to still meet the 2035 target and preserve biodiversity. Clear-cutting reduces biodiversity and carbon sequestration, which is why the rotation period of the tree stand should preferably be prolonged. Excessive clearing of the site removes nutrients needed by the organisms and can therefore have a negative impact on the environment. Planting too many of the same species in one area monoculturally is also problematic for biodiversity and harmful species. Various fungal diseases and pests easily spread to nearby trees of the same species and, in the worst case, can destroy the forest in the area. However, through sustainable forest management, the condition and biodiversity of forests can be improved. (Luke 2023c; IEA 2023b, 53.)

Other areas of the LULUCF (*Land Use, Land Use Change and Forestry*) sector should also be considered, such as restoring drained peatlands and reducing agricultural emissions. These have increased especially in the last two decades. Greenhouse gas and particulate emissions at different stages of the biomass supply chain must also be considered. (IEA 2023b, 53.)

Most of the total emissions come from the energy sector. If total carbon dioxide emissions in 2020 were about just over 40 $MtCO_2$ the total emissions were 47.8 $MtCO_2eq$. This is about 1.4% of the total EU27 emissions. On the other hand, in terms of emissions per capita, the average Finnish produced more emissions than the average EU citizen, as a Finn produced on average 8.6 tCO_2eq and a EU citizen 7.4 tCO_2eq. The reasons for this are, the colder climate in Finland and strong industrial sector, which cause an increase in energy demand. In addition, food production and the transport sector are also responsible for high emissions. Finland has long distances and a high proportion of rural population compared to other EU countries, which means that private transportation is quite high. The total energy consumption of transport in Finland in 2021 was about 170 PJ, of which road transport accounted for about 93%. So improving the energy sector is important in terms of emissions, because that is where most of the emissions come from. (Statistics Finland 2022a, 18; Statistics Finland 2022b; Hyppönen & al. 2022, 50.)

3.5.4 Social aspect

From the social aspect of biomass use, it is important to assess its impact on the social environment. Biomass utilisation often contributes to rural prosperity and creates jobs, which will have a positive influence on the development and economy of the region, as in Finland.

Countries with domestic biomass can also increase their self-sufficiency by, for example, divesting from imported fossil fuels and replacing them with bioenergy and other renewables. The sustainability of land use must be ensured so that natural ecosystems and food production do not suffer. Regional planning and decision-making processes need to be open to everyone. In addition, pollutants such as particulates, nitrogen oxides, sulphur oxides and carbon monoxide are produced during biomass utilisation like in combustion processes and can be harmful to health. These can be controlled by emission control equipment and techniques. EU Commission Regulation 2015/1189 sets out ecodesign requirements for boilers burning solid fuels to set limits on the emissions to reduce solid fuel boilers impact on air quality as well as on climate change. (IEA 2017, 11-12, 49; Thrän & al. 2020 5; IIASA 2012, 302; European Commission 2015.)

In terms of social sustainability, stakeholder engagement is also crucial. Stakeholders such as public authorities, political parties, non-governmental parties, local industry and local communities are part of the engagement process during the planning, implementation and monitoring phases of the projects. This helps social sustainability by resulting in better outcomes and social acceptance. (IEA 2017, 65, 77-78.) Factor that can affect social acceptance include people's knowledge of the issue. For example, in a study on biofuels for transport conducted in Finland in 2017, the more people had knowledge about renewable fuel options such as hybrid, electric or hydrogen vehicles, the more likely they were to be interested in them as an option. Another important factor was the knowledge of the environmental problems caused by fossil fuels. (Moula & al. 2017.)

The use of biomass must also take into account the political implications, such as EU restrictions, in which case Finland may face the risk of having to reduce the use of biomass for energy. In Australia, for example, biomass has been excluded from the renewables in 2022. If the EU were to do so, it could hamper the development of bioenergy in Finland and could lead, in the worst case, to a return to fossil fuels, which would of course not be desirable. In the latest update of the EU RED, subsidies for harvesting roundwood for energy production are at least prohibited. (Catanoso 2023.)

4 Biomass as a replacement for fossil fuels in the current energy system

To achieve carbon neutrality in Finland, replacing fossil fuels is an ambitious challenge that will require several energy sources to contribute. Biomass has and will continue to play a significant role in Finland as a replacement for fossil fuels. New technologies, research and development have been rapid and have enabled the use of bioenergy in different sectors. Bioenergy has accounted for about 40% of renewable energy in the EU and about 80% in Finland. It is evident that bioenergy has been playing an important role in achieving the current climate targets. In Finland, biomass is mostly used as a fuel in heat production and industrial processes. (Tuohiniitty & Laurikka 2021.) For example, in electricity and heat production, biomass has been used to replace coal, which is to be phased out by 2029 (TEM 2019). In transport, there have also been efforts to replace fossil fuels with electric vehicles and bio-based fuels, such as renewable biodiesel and bioethanol, but fossil fuels are dominant (Statistics Finland 2022a, 43).

According to an IEA study, the total energy supply in Finland in 2021 was about 1390 PJ, of which coal accounted for 6.3%, oil for 20.8% and natural gas for 6.4%. Biofuels and waste accounted for 33.6%. Figure 12 shows the supply of each fossil fuel at approximately ten-year intervals from 1973 to 2021, as well as biofuels and waste and total energy supply. (IEA 2023b, 184.)

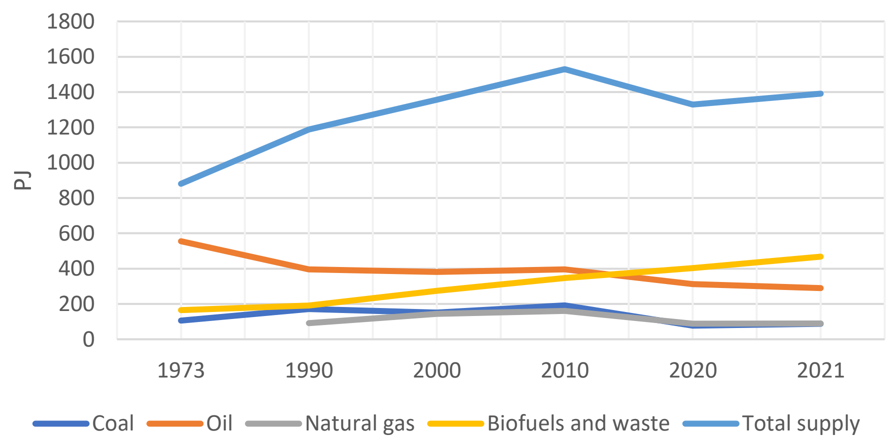

Figure 12. Total energy supply of fossil fuels in addition to biofuels and waste from 1973 to 2021 (IEA 2023b, 184).

The supply of coal, oil and natural gas has gradually decreased over time, especially from 2010 onwards, while the share of biofuels and waste has increased. It can be noted that biofuels have at least been part of the reduction in fossil fuel use, as the total energy supply has remained more or less the same during the 2000s. Other renewable energy sources will also increase their share. (IEA 2023b, 184.)

Oil has accounted for the largest share of total energy supply from fossil fuels, while natural gas and coal have been lower. Most fossil oil is used in the transport and industrial sectors. In transport, oil is needed to produce fuels such as gasoline and diesel and in industry in certain sectors, such as the chemical industry. However, oil is expected to decline considerably in the transport and industrial sectors in the future due to new policies by the Finnish government to improve the role of alternative, less polluting fuels. Oil for heating is targeted by the government to be phased out by 2030 through a biofuel blending obligation for light fuel oils. (IEA 2023b, 173-175, 184.)

Coal in turn has mainly been used in Finland for electricity and heat production, and also as a fuel for industry, a total of 2015 thousand tons in 2022. The trend in coal use has been downwards and as mentioned earlier, coal is expected to be phased out by 2029. In 2022, about 50% less coal was consumed than the average for the 2000s, although its use increased slightly due to the energy crisis caused by the Russian war in Ukraine to replace imported electricity and natural gas. Nevertheless, renewable energy sources such as biomass in Finland have been used to replace coal in energy production even before the war. (Statistics Finland 2023.)

Natural gas has played a relatively small role in Finland's energy mix compared to some other EU countries, such as Germany and Italy. Before the Russian war in Ukraine in 2022, Russia supplied most of Finland's natural gas. Therefore, natural gas was replaced by alternatives such as coal, biomass and propane, as well as with energy efficiency measures. Consequently, natural gas consumption fell by 50% in 2022. However, to ensure future supply of natural gas, there have been steps to increase imports of LNG. A new floating LNG storage and regasification unit has just been completed at the port of Inkoo in December 2022 and was taken into commercial operation in January 2023. However, in the long term, it is expected that policy measures will lead to the replacement of natural gas by other sources such as renewable gases, like biogas, and low-carbon hydrogen. (IEA 2022b, 159.)

4.1 Transport

Since the 1970s, energy consumption in the transport sector has more than doubled compared to current consumption to almost 200 PJ. The majority of this consumption is due to road transport, and the remainder shared among marine, aviation and railway transport. In 2021, the total energy consumed in road transport in Finland was around 160 PJ, which has remained fairly stable over the last 10 years, except for a small downturn in 2020 due to covid-19 pandemic. Around 80% of fuel consumption in road transport was from fossil fuels. The largest share was for fossil diesel and the second largest for gasoline. Renewable diesel, in turn, had by far the largest share of renewable fuels. Figure 13 shows the shares of different fuels from 2010 to 2021. (Statistics Finland 2022a, 42-43.)

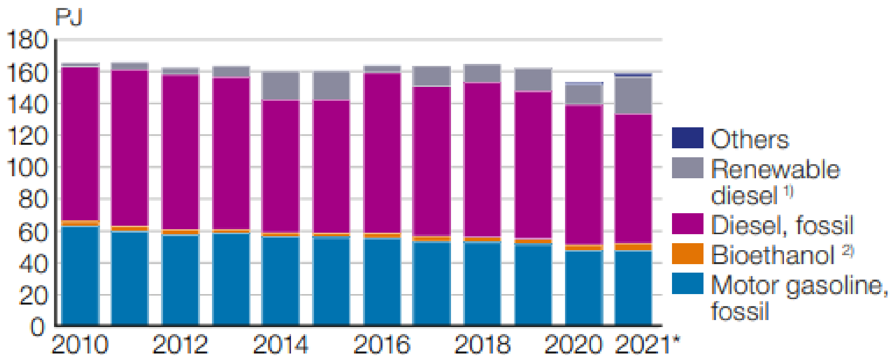

Figure 13. Fuel consumption in road transport from 2010 to 2021 (Statistics Finland 2022a, 43).

Renewable diesel has gradually started to replace fossil diesel, which is still widely used. In this context, renewable diesel refers mainly to second generation biodiesel and to a small extent to first generation biodiesel produced by the FAME (*Fatty Acid Methyl Esters*) esterification process. Second generation biodiesel is produced by HVO (*Hydrotreated Vegetable Oils*) hydroprocessing of oils and fats, which is suitable as a fuel on its own for all diesel engines or blended even at high blend ratios with fossil diesel. For example, a Finnish team from Neste Oyj just won the 2023 European Inventor Award for a technology that converts waste oils and fats into high-quality renewable products, such as renewable diesel. The UPM biorefinery in Lappeenranta has, in turn, been producing renewable wood-based diesel and naphtha since 2015. UPM is also planning the possibility of a biorefinery in Kotka, which would produce an estimated 500 000 tons of advanced biofuels for transportation. In Finland, a lot of development work is being done to expand the raw material base and improving the manufacturing processes. (Statistics Finland 2022a, 43; Suojanen 2023; IEA Bioenergy 2021a, 16.)

In Finland, bioethanol is usually produced by a fermentation process from forest industry residues, such as starch and cellulose. Bioethanol is typically used blended at a low ratio with fossil gasoline. For conventional internal combustion engines, the maximum blend ratio is 10% ethanol in gasoline. High-grade ethanol E85, which contains up to 85% ethanol, can only be used in internal combustion engines that can use higher ethanol levels, such as flexfuel internal combustion engine vehicles. In Finland, St1 Biofuels Oy currently produces 10 million litres of bioethanol annually from sawdust residues in Kajaani. In addition, a plant producing 50 million litres of bioethanol per year is planned in Pietarsaari. (Hyppönen & al. 2022, 29; IEA 2023b, 93; IEA Bioenergy 2021a, 16.)

Other fuels in the diagram in figure 13 include biogas and electric vehicles. The share of biogas in transport has remained quite small, around 0.8% of all renewable fuels in transport, as most of the biogas produced in Finland is used for electricity and heat production. Biogas is mainly produced from biowaste and sewage sludge, but biogas from agricultural biomass is currently estimated to have the greatest untapped potential. Biogas for transport is refined by purifying it to almost pure methane, removing carbon dioxide, hydrogen sulphide and moisture. Refined biomethane for transport accounted for 20% of the biogas produced in 2021. The Finnish Biogas and Bioenergy Association has estimated that in 2030 more than 70% of the biogas produced would be processed into biomethane, which could be used in vehicles, ships and industry, and transported in the gas network. Biogas production in 2021 was around 1 TWh and in 2030 the target is 4 TWh. The annual biogas production potential in Finland using digestion technology is estimated at 10-25 TWh per year. (IEA 2023b, 93; Suomen Biokierto ja Biokaasu ry 2022.)

Compared to the EU Member States, Finland has an ageing and slowly renewing car fleet. Electric and hydrogen powered vehicles can be expected to increase their share as a replacement for fossil-fuelled vehicles in the future, but biofuels can play a role in reducing emissions now. Finland currently has a lot of mature technology, expertise and research and development, as well as existing infrastructure for biofuel use. The growth of biofuels in the transport sector is driven by the 2030 target set in 2019 of 30% biofuel distribution obligation, which is currently Finland's main measure to promote renewable fuels in transport. To this was also added the sub-requirement of a minimum 10% distribution obligation for advanced biofuels. However, in April 2022, the distribution obligation requirements were eased for the period 2022-2023 due to the reduced energy supply caused by the Russian war in Ukraine and tightened from 30% to 34% in 2030. (Bioenergia ry 2020, 21; IEA 2023b, 93-94.)

Finland is striving to increase the use of biogas in transportation due to its great production potential. Most of the support under the Energy Aid programme was granted to projects related to the use of biomethane in transport between 2018 and 2021. The target for biogas use in transport is 2.5 TWh by 2030 and 5-6 TWh by 2045. At the end of 2021, the total number of passenger cars in Finland was about 2.8 million. 2.5 TWh of biogas would be enough to fuel an estimated 100 000-130 000 passenger cars and 6000 heavy transport. However, in the long term, Finland's goal is to almost completely electrify passenger cars and rail transport. Liquid and gaseous biofuels, hydrogen and some degree of electrification are seen as solutions for heavy road transport, marine transport and aviation. Hydrogen cells are more energy efficient, but mature technology and infrastructure for biofuels already exists. From hydrogen, on the other hand, it is possible to produce a zero-emission fuel, so-called green hydrogen through electrolysis with renewable electricity, which may have great potential in the future. (IEA 2023b, 93-94; Statistics Finland 2022a, 41; Hyppönen & al. 2022, 31.)

4.2 Heating and cooling

District heat use in Finland is among the highest in Europe after Denmark and Estonia in TFEC (*Total Final Energy* Consumption). Its use is mostly dominated by the heating of buildings, where it is the primary heat source, accounting for 45% and in industry 10%. District heating is commonly used in densely populated areas. Total district heat supply in the 2000s has remained between 170-200 PJ, with the exception of the 211 PJ minor peak in 2010, which can be seen in figure 14. Most district heat is produced by CHP (*Combined Heat and Power*) plants (60%) and the rest by heat-only plants and a small proportion by heat recovery, which includes, for example, heat pumps. (IEA 2023b, 69; Statistics Finland 2022a, 39.)

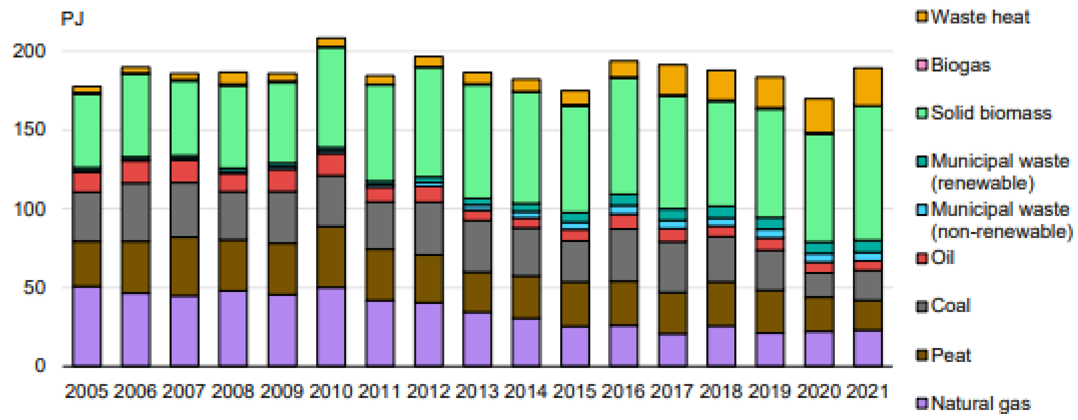

Figure 14. District heat production by fuel 2005-2021 (IEA 2023b, 69).

In 2021, the supply of district heat was about 190 PJ and cooling 1.2 PJ. The use of renewable fuels for heating has been steadily increasing, driven largely by wood fuels, while the share of fossil fuels has been declining. The use of peat in energy production is also to be reduced because of its negative climate impact. Peat is not a fossil fuel, but it is equated with them in EU emissions calculations because of its slow renewal rate. Replacing Russian imports and rising natural gas price, in turn, increased the use of coal in 2022. Either way, coal use is in decline. (IEA 2023b, 69; Hyppönen & al. 2022, 25; Energiateollisuus ry 2023a.)

Solid biomass is by far the most widely used renewable energy source as a fuel for heat production. Solid biofuels used in Finland include forest residues, firewood, wood processing residues, pellets and briquettes, and recycled wood. Pellets and briquettes are cylindrical compressed biofuels typically made from wood residues, but can also be made from fresh biomass, in which case drying is also required in addition to crushing. This improves the fuel properties of biomass. The fuel properties of biomass can also be improved by torrefaction, the roasting of biomass without oxygen to make it more coal-like fuel. Biomass torrefaction combined with pelletisation can produce high-quality biocoal. In Finland, for example, the Joensuu Biocoal Oy project company is building a plant producing torrefied biomass, which is expected to be completed by the end of 2023. It would produce around 60 000 tons of torrefied biomass per year to replace fossil coal in industry and energy production. In addition, the heat generated during the process could be used in a dryer or fed into the district heating network. Biocoal could be used directly as a substitute for coal without major modifications, while pellets, for example, can be blended with 5-10% of coal (CEA 2018, 1). However, Finland is phasing out coal completely by 2029. Burning other biomass in coal-fired boilers requires major changes. However, torrefaction is still a relatively new technology, and its profitability is affected by factors such as production costs and the availability of raw materials, which are also in competition with other bio-based products. (IEA 2023b, 69, 91-92; VTT 2016, 66; Joensuu Biocoal 2023.)

The use of waste heat in district heating has increased, especially over the last 10 years. In 2021, the share of waste heat was 12%. Waste heat can be recovered from industrial processes and facilities, such as from the forest industry, and from condensing plats. In Finland, waste heat is estimated to be generated about 470 PJ and reasonably recoverable about 125 PJ. As technologies develop, the importance of heat pumps is expected to grow further in the future as part of a carbon-neutral energy system. New technologies could make it possible to exploit previously unprofitable heat sources. (IEA 2023b, 69, 70; TEM 2023.)

Renewable municipal waste comes from households and is also collected as part of municipal waste. The use of municipal waste in heat production has increased slightly over the last 10 years. There may be untapped potential in the use of renewable municipal waste for bioenergy if more efficient recycling can be achieved. However, waste is more challenging to process than other raw materials because of its mixed and heterogeneous composition. The collected biowaste can be used to produce biogas. (IEA 2023b, 69; Suomen Biokerto ja Biokaasu ry 2022.)

The use of biogas in heat production has so far remained rather modest. In 2021, 60% of Finland's total biogas production of 1 TWh was used for heat production. In 2030, the majority of biogas produced will be refined into biomethane and allocated to the transport sector, an estimated 2.5 TWh out of 4 TWh. (Suomen Biokerto ja Biokaasu ry 2022.)

In Finland, oil heating is not primarily used for district heating, but it is estimated that around 130 000 residential buildings and around 5100 municipal buildings use oil heating. Together, they result in carbon dioxide emissions of around 900 kilotons per year. In Finland, oil heating is aimed to be phased out in buildings by the early 2030s and in public buildings by 2024. The government programme sets out 26 measures to replace private and public oil heating with other forms. These measures are supported by various grants and subsidies. For example, grants of up to 4000 euros have been granted to private house owners to help them switch from oil heating, if they switch to geothermal heat pumps, air-to-water heat pumps or district heating. (YM 2021; IEA 2023b, 68.)

Biomass has probably the best potential for use in heat generation and industrial processes. District heat production in Finland is largely based on combustion-based technologies, where biomass has played a growing role as a replacement for fossil fuels, especially in CHP plants. It might also be possible to integrate methane and hydrogen production units into CHP plants, for example, and recover waste heat for district heating. Combined with bioenergy carbon capture and utilisation (BECCU), for example in hydrogen production, emissions can be reduced, or carbon neutrality can be achieved through bioenergy carbon capture and storage (BECCS). For now, carbon capture technology is quite complex and expensive, making it most profitable to use in large units. In Finland, BECCS technology could be attractive and have potential, as there are many large-scale biomass-based industry and facilities. This could also allow the production of carbon-negative district heating. (Hyppönen & al. 2022, 47.) Currently, some technologies for carbon capture and utilisation are in use in Finland, such as Carbon2X concept in Riihimäki, which is a common pilot project of Fortum and Q Power to produce methane from carbon dioxide and hydrogen for the production of special plastics. (Välinen 2022.)

4.3 Electricity

In 2021, electricity generation in Finland was 69 TWh and total consumption 87 TWh. The share of renewables in Finland's electricity generation has grown considerably over the past years. In 2021, renewables represented 53% and fossil-free 86% of total generation. Most of the increased renewable generation has been due to wind power over the last 10 years. In 2021, 12% of electricity was generated by wind power. The use of hydropower and bioenergy, in turn, has remained fairly stable with slight variations. In 2021, hydropower accounted for 23% and renewable fuels for 18% of total electricity generation. Renewable fuels mainly refer to biofuels, such as solid forest biomass with some biogas and renewable waste. Nuclear power accounted for 33% of electricity generation and has remained fairly stable over the last 20 years. (Statistics Finland 2022c; IEA 2023b, 87.)

The share of coal and natural gas in electricity generation has fallen significantly over the last 20 years. In 2021, both accounted for about 5%, together 10%, of total generation. In contrast, between 2000 and 2010, together with peat, fossil fuels have accounted for 30-50%

of total generation. Figure 15 below shows Finland's electricity generation 2000-2021. (Statistics Finland 2022c; IEA 2023b, 186.)

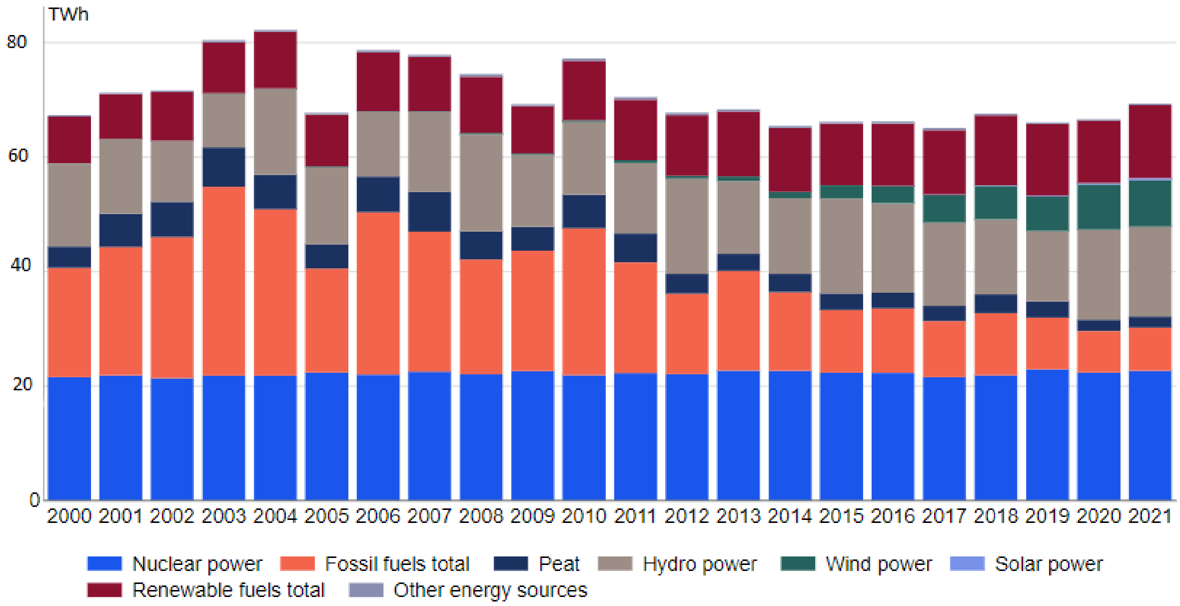

Figure 15. Electricity generation in Finland 1970-2021 (Statistics Finland 2022c).

The main changes in electricity generation in 2022 was a 76% increase in wind capacity and a 41% increase in wind generation. In May 2022, imports of electricity from Russia were ended. In 2022, natural gas use decreased by almost 4% compared to the previous year, while coal use increased by around 1%, in part to compensate for the reduced use of natural gas. In addition, the share of nuclear power and thus fossil-free electricity generation has increased with the operation of Olkiluoto 3, which started regular electricity generation in April 2023. Therefore, the share of nuclear power increased by 7%. (Energiateollisuus ry 2023b; STT 2023.)

Bioelectricity, the second largest share of renewables, is mainly produced from solid biomass. The majority of bioelectricity is produced with CHP plants. The share of bioenergy in electricity generation has not changed much over the last 20 years, as wind power has grown rapidly and nuclear power has had a large share. Wind power capacity is expected to grow to 6.8 GW by 2030, whereas in 2022 it was 3.6 GW. In order to increase renewable production, Finland has offered investment subsidies for the projects of new technologies and small-scale distributed renewables deployment, such as feed-in tariffs. However, they were no longer offered after 2017 for wind power, 2019 for biogas and 2021 for wood chip power plants. Since then no more subsidies have been granted for new projects, as the rest of the investment is considered to be market-driven. Almost all of the 2019-2021 feed-in tariff payments went to wind power projects. (IEA 2023b, 87-88; IEA Bioenergy 2021b, 9.)

Other renewables may compete more with the profitability of the biomass in electricity sector. So, biomass may make the most potential for heat production, transport biofuels and industrial sectors. The aim in Finland is to encourage the conversion of heat-only plants into CHP plants, when it is feasible and economically viable. Finland's electricity consumption is expected to increase in the future, which will be partly moderated by increased energy efficiency, which, for example, CHP plants contribute to. In 2030, Finland's electricity consumption is expected to be around 90.3 TWh and in 2050 100 TWh. The main drivers for the growth in electricity consumption are digitalisation and thus the resulting increase in data center capacity, the electrification of transport and the electrification of greenhouse gas emitting industrial processes where possible. As electricity consumption increases, it could therefore be profitable to increase the share of CHP plants, although the study commissioned by TEM assumes that the number of CHP plants will slightly decrease or remain the same from now to 2050. For biomass utilisation in CHP plants, Finland has familiar and mature conversion technologies and a lot of knowledge. (Bioenergia ry 2020, 32; TEM 2019, 6.)

As variable renewable energy increases in the power system, electricity storage solutions will be needed to shift generation more evenly. Biomass as an energy carrier has the advantage of being relatively easy to store and transport and flexible to use when needed, and the possibility of CHP plants to produce heat alongside electricity. In the future as technology develops, hydrogen is expected to provide a solution as a new form of energy storage for surplus electricity by electrolysis. Hydrogen and oxygen are produced from water by electrolysis, and the hydrogen can be stored until it is used to produce electricity and heat by fuel cells or gas turbines. In addition, it could be possible to recover waste heat from electrolysis to improve efficiency. The role of hydrogen would be particularly important in areas where electrification would be challenging. (Hyppönen & al. 2022, 30, 46-47.)

4.4 Industry

Industry is the most energy-consuming sector in Finland. In 2021, it consumed 36% of total energy consumption and 52% of total final energy consumption, which is higher than the European average. Between 2011 and 2021, the share of bioenergy and waste increased 9%, while the shares of oil, coal, peat, electricity and district heating decreased gradually. The use of natural gas has remained fairly stable, but it is still relatively low compared to other European countries. Figure 16 shows total final energy consumption in Finnish industry 2005-2021 by source and sector. (IEA 2023b, 62; Statistics Finland 2022a, 45.)

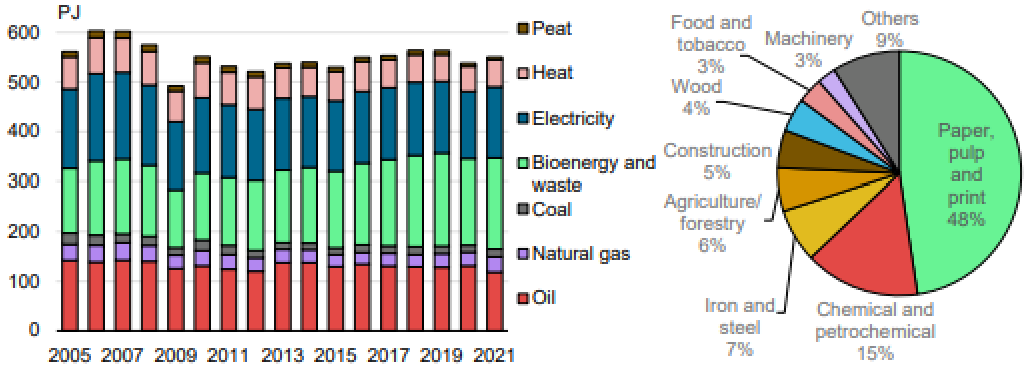

Figure 16. TFEC in Finnish industry in 2005-2021 by source and sector (IEA 2023b, 63).

The increase in bioenergy and biowaste is mainly due to the increased recovery of waste and by-products, which has also been responsible for the increase in biomass use in other sectors. Traditionally, wood fuels have been an important replacement for fossil fuels and peat in Finland. One of the most important forest industry by-products used in energy production is black liquor, a by-product of pulp production. By sector of industry, as shown in figure 16, paper, pulp and print industry are by far the most energy consuming sectors with 48% of TFEC. Finland is together with Sweden the biggest pulp producing countries in Europe. The next largest energy consuming industries are chemical and petrochemical industry by 15% and iron and steel by 7%. The forest industry being the largest consumer of industrial energy, also uses its own fuels for energy production. Black liquor and other waste sludge are important fuels for the forest industry, and they produced a total of about 166 PJ of energy in 2021. (IEA 2023b, 62-63; MMM 2023.)

Industry produced 188 PJ of heat in 2021, of which 79% was produced with renewables. Black liquor accounts for 52% of the heat produced by industry. On the other hand, part of industrial heat use is already accounted for as fuel consumption, so it is not included in industrial heat consumption. (Statistics Finland, 2022c.)

The forest industry is expected to grow in the future, which would also mean an increase in energy consumption. At the same time, the aim is to limit the growth in consumption by increasing energy efficiency as part of the progress towards carbon neutrality by 2035. The aim is to increase energy efficiency, for example by electrifying where possible and by recovering waste heat. (IEA 2023b, 63.)

Hydrogen is likely to play an important role in reducing emissions from industry, especially in the steel and chemical industries. The hydrogen needed for industry is produced from 96% fossil raw materials. For example, SSAB plans to convert its steel products to fossil-free in Finland and Sweden by using hydrogen instead of coal in the reduction of iron ore. SSAB's steel plant in Raahe is responsible for 7% of Finland's emissions and is the largest source of emissions in Finland. Fortum and SSAB are currently investigating how to produce sponge iron from fossil-free hydrogen. Fortum is studying the technical and economic feasibility of a possible 700 MW hydrogen plant. (Hyppönen & al. 2022, 30; Lampila 2020; Fortum Oyj 2023.)

The annual production of hydrogen in Finland is 140 000-150 000 tonnes, corresponding to about 4.7-5 TWh. 88% of hydrogen is used to refine oil and biofuels. Major users in Finland are Neste in Porvoo and the UPM biofuel production plant in Lappeenranta. Hydrogen can also be sourced as a by-product from some forestry and chemical industry processes like pyrolysis and gasification. Alternatively, if emitting hydrogen production is combined with carbon capture and storage, its emissions would be largely neutralised. In addition, waste heat from hydrogen production could be utilised to increase industrial heat production. (Lampila 2020; Valtioneuvosto 2023a, 9.)

5 Renewable and bioenergy policy

Finland's main climate goal is to become the world's first carbon-neutral welfare society by 2035, after which the goal may even be carbon negativity (IEA Bioenergy 2021, 3). Under EU legislation, Finland has an obligation to reduce greenhouse gas emissions by 39% from 2005 levels by 2030. The main driver for Finland's climate policy is the national Climate Change Act. A new Climate Change Act, which entered into force in July 2022, set emission reduction targets for 2030, 2040 and 2050. Also carbon neutrality target for 2035 was included. For 2030, the target is -60% of 1990 levels, for 2040 -80% and for 2050 at least -90%, with a target of -95%. These emission reduction targets are based on the recommendations of the Finnish Climate Change Panel. In addition, for the first time, the aim to increase acts to strengthen carbon sinks was mentioned. Figure 17 shows the amounts of carbon dioxide emissions and sinks in million tonnes of carbon dioxide equivalent from 1990 estimated to 2050. (Valtiokonttori 2023.)

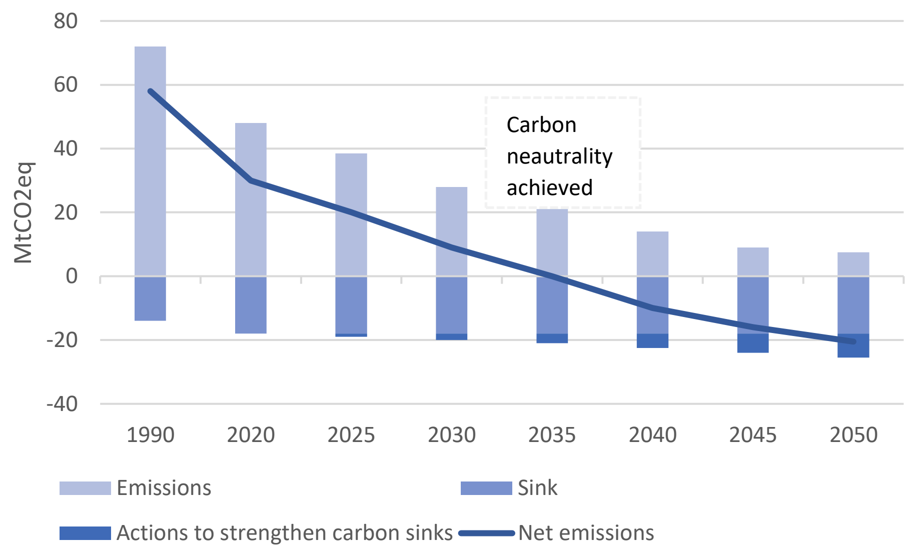

Figure 17. Finland’s carbon dioxide emissions and sinks 1990-2050 (adapted Valtiokonttori 2023).

The new Climate Change Act was also expanded to cover emissions from the land use sector. In 2021, the LULUCF (*Land Use and Land Use Change and Forestry*) sector became a net emitter for the first time, which means that more carbon dioxide is emitted than is absorbed. The reason for this is assumed to be that forests are harvested faster in relation they grow, which would require more emission reductions from other sectors. (Valtiokonttori 2023.) As part of the Fit for 55 package, the European Commission proposed a review of the RED II Renewable Energy Directive, which was adopted in 2018. The European Parliament voted in September 2022 to cap or limit subsidies for the use of primary wood for energy production to meet the 2030 renewable targets of 32%. On the other hand, most of Finland's energy wood is forestry residues, which would not be affected, but 11% of primary wood is estimated to be used for energy. (IEA 2023b, 84; Statistics Finland 2022a, 8.)

Finland's national climate legislation is based on the UN Framework Convention on Climate Change and the EU's obligations. The European Climate Law entered into force in July 2021. The EU's goal is to achieve carbon neutrality by 2050 and reduce emissions by at least 55% compared to 1990 levels. Finland has set its own targets a little further than the EU, as earlier mentioned. (Statistics Finland 2022a, 8.)

In December 2019, the Council of Europe and the European Commission set up the European Green Deal. It is a set of initiatives to contribute to the EU's fight against climate change and to help achieve carbon neutrality targets, reinforced by the European Climate Law. The 55 package is a set of proposals to update the EU's climate policy and help the EU meet its targets, which was adopted in July 2021 by the European Commission. 55 refers to the 2030 emission reduction target. (TEM 2022b, 15; European Council 2023.)

Proposals include a review of the ETS (*Emissions Trading System*) sector, which is a policy tool for reducing greenhouse gas emissions by setting caps on the sectors and industries covered by the system. The latest review focused on its extension to maritime transport and a separate emissions trading scheme for road transport and buildings. In December 2022, the Council reached a preliminary agreement with the European Parliament to increase the emission reduction target for ETS sectors to 62% by 2030. In Finland, energy-intensive industry and electricity generation are regulated by the EU ETS. (European Council 2023; IEA 2023b, 23.)

For the non-ETS sector’s emissions, renewable energy and energy efficiency as well as for border crossing electricity connections targets are defined in Finland's National Energy and Climate Plan (NECP). Finland's renewable energy targets for 2020 and 2030, and their implementation in 2021 in different sectors, are presented in table 1. (IEA 2023b, 23-24.)

Table 1. Finland's renewable energy targets for 2020 and 2030, and their implementation in 2021 (IEA 2023b, 24).

	2021 status	2020 targets	2030 targets
Electricity	39 %	41 %	53 %
Heating & cooling	53 %	54 %	61 %
Transport	21 %	10 %	45 %
Gross final energy consumption	43 %	38 %	51 %

Finland has set higher targets than the EU with targets of 32% renewable energy and 14% renewables in transport by 2030 (European Commission 2023a). However, it has been proposed to increase the share of renewable energy to at least 40% from 32% in the 55 package (European Council 2023). Finland's progress towards meeting its targets has been relatively in line with expectations. (IEA 2023b, 24; Statistic Finland 2022a, 8.)

In July 2021, an EU energy efficiency target of 9% by 2030 was proposed by the Commission for the 2020 reference scenario, which would correspond to 36% of final energy consumption and 39% of primary energy consumption compared to the 2007 reference scenario. However, in May 2022 the Commission proposed raising the energy efficiency target to 13%, but in July 2023 a binding target of 11.7% was set. (European Commission 2023b.) With 9% energy efficiency target, Finland's primary energy consumption would be 1296 PJ and final energy consumption 900 PJ in 2030. With 11.7% energy efficiency target, in turn, primary energy consumption would be 1258 PJ and final energy consumption 873 PJ in 2030. (IEA 2023b, 60.) Improving the energy efficiency of buildings is also part of the 55 package. 40% of the EU's total energy consumption was consumed in buildings, while in Finland about one third. The latest EU regulations aim for new buildings to be emission-free by 2030 and existing buildings by 2050. (European Council 2023; IEA 2023b, 65.)

The 55 package sets targets for reducing emissions from road transport as well as from maritime transport and aviation. In the transport sector, there is great potential for reducing emissions, as the vast majority of fuels used are fossil fuels. The ReFuelEU Aviation and ReFuelEU Maritime proposals for aviation and maritime transport, respectively, aim to promote climate objectives and increase the use of more environmentally friendly fuels. The aim in maritime transport is to increase the use of renewable and low-carbon fuels to reduce greenhouse gas emissions by 75% by 2050. Passenger cars and vans account for about 15%

of all emissions in Europe and almost as much in Finland relative to its own emissions. (European Council 2023; Statistics Finland 2022a, 19, 41-42.)

The above-mentioned acts are examples of how the EU influences decision-making at national level in Finland. Finland's new Government Programme, which was published in June 2023, states that the Government intends to maintain an environment for bioenergy through national decisions and EU influence that is steady and predictable. The main feedstocks for biofuels are residues, by-products and wastes, which should be used as a priority. The government also considers it important to promote efforts to make Finland a leading producer and developer of bio-based products, as bioenergy is believed to play a major role in replacing fossil fuels. For example, progress will be made in biogas development and use, supported by distribution obligations and capacity mechanisms. On a small scale, the intention is to create the conditions for farm-scale biogas production and the possibility of building a biogas network between farms and business. Finland is also believed to have a competitive advantage in terms of carbon capture due to its large forest industry and abundant use of bioenergy. The government has stated that it will set targets for the use of carbon capture within the 2020s. (Valtioneuvosto 2023b.)

However, the government's policies are believed to slightly slow down the uptake of renewable fuels for transport. Although there have been mentions of promoting biogas and electric fuels, among other things, the new government will loosen the distribution obligation for renewable fuels imposed by previous governments. This is expected to reduce drivers and create some uncertainty for the production of renewable fuels. (Valtioneuvosto 2023b.)

Finland's recycling rate has been below the EU average. Although progress has been made, it has been quite slow. The circular economy is seen as an important tool for guiding Finland towards sustainability. The circular economy is promoted, for example through the separate collection and recycling of bio-based materials and biodegradable products. This will also contribute to Finland's self-sufficiency by making more use of the material. The circular economy will create new jobs and businesses in Finland. As Finland strives to become carbon neutral by 2035, it also aims to become a leader in the circular economy by 2035. The aim is to double the circular economy rate of materials and double resource productivity by 2035. (Valtioneuvosto 2023b; Kaariaho & Pirtonen 2022.)

Finland's support for renewables has moved from operation-based to investment-based subsidies. Under the operation-based support system, subsidies were paid based on the amount of energy produced, but in the investment-based system, subsidies are paid for successfully completed projects. The aim is to commercialise, lower the cost of new technology and small-scale distributed production. Finland's renewable feed-in tariff scheme for heat and electricity production was ended for new projects for different technologies systematically in 2017-2021. Currently, Energy Aid is the main investment programme granting investment subsidies in Finland. For example, grants are given for 25% of biogas project costs, for wood fuel heating 10% and for landfill gas and small CHP 15%. (IEA 2023b, 84.)

6 Future potential of biomass as a replacement for fossil fuels

Biomass, especially solid wood-based, has so far been largely responsible for replacing fossil fuels with renewable energy in Finland. Its share has risen in the last decade. In addition to solid biofuels for industry, electricity and heat production, the growth in total bioenergy supply has been driven by biofuels in other forms such as biogas, liquid biofuels and renewable municipal waste. Figure 18 shows the total bioenergy supply in Finland from 2000 to 2019, classified by biofuel type. (IEA Bioenergy 2021b, 6.)

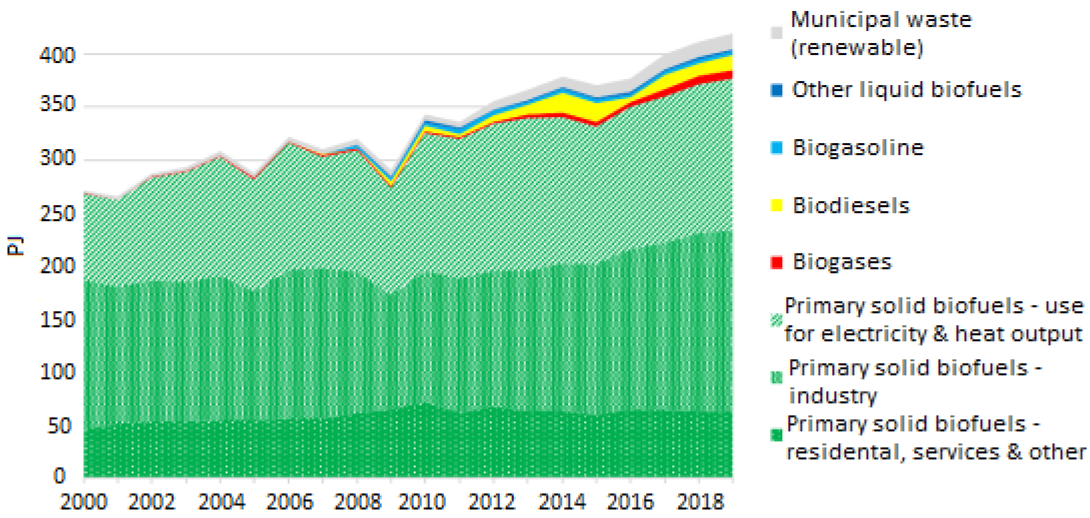

Figure 18. Total bioenergy supply in Finland from 2000 to 2019 (IEA Bioenergy 2021b, 6).

Bioenergy accounts for almost a third of total energy supply (IEA Bioenergy 2021b, 5). Direct replacement of fossil fuels would require more than 500 PJ of additional fossil-free energy (Michaux & al. 2022, 6). According to the Natural Resources Institute Finland, sustainable annual forest harvest is estimated at 80.5 Mm^3, which current logging volumes are close to (Luke 2023c). There are concerns that the future demand for biomass in both energy production and industry will grow beyond sustainable production while trying to meet carbon neutrality targets. There has been much discussion recently in Finland about possible restrictions on the use of forest biomass due to conservation, risk of over-harvesting and reduced imports from Russia. The EU's third RED update RED III mentions some new soil and forest protection measures. These include the prohibition of biomass subsidies for harvested roundwood, which should preferably be used to produce more valuable wood products. In addition, subsidies would also be prohibited for the harvesting of roots and stems, which, when left in the ground, protect the carbon sequestered in the soil. (Catanoso 2023.)

A study by Material Economics, the Energy Transitions Commission and the European Forest Institute (EFI) estimates that climate actions could even double the demand for biomass in the EU by 2050, for which biomass resources will not be sufficient. For this reason, the use of biomass feedstocks should be considered carefully. It has been discussed that more biomass feedstocks should be directed to the production of high quality materials instead of energy production. (Hassinen 2021.)

Finland has a lot of bio-knowledge and technology. Although, Finland is rich in forest biomass, there is hardly room for increasing harvesting. The way to significantly increase the use of woody biomass in energy production is to reduce the amount of biomass used by the forest industry, which is not a real solution. The potential for increasing the production of other biomass sources should be considered. (Hassinen 2021; Michaux & al. 2022, 6-8.)

In energy production, the aim is to use woody biomass that is not used by the forest industry. This has helped to increase the use of woody biomass for energy production before. The most important by-products and residues from the forest industry are black liquor, bark and sawdust, although these have already been almost fully exploited. Similarly, recycled wood is a commonly used source of energy, which has seen the largest relative increase in the last decade. In Finland, recycled wood is used relatively well for energy production, as in Sweden. However, Sweden is also making more use of imported wood waste fractions. With new technological investments and solutions, there could be more potential for utilising wood waste fractions on the site of use in Finland too. In addition, integrated harvesting has made it possible to improve the recovery of forest chips at the point of harvest by separating the wood material for industrial and energy production. Technological developments are also expected to bring improvements, such as the efficient use of waste heat or the possibility of using lower-quality material, like material with a higher moisture content. (Motiva 2023a; Maukonen 2023.)

The potential for the use of agrobiomass is believed to be high. The advantage of agrobiomass would be its ability to be increased quickly. In Sweden, for example, the use of agrobiomass is higher, estimated to be as high as 195 PJ by 2050, which is about 46% of current bioenergy consumption. According to studies, the additional potential from agricultural by-products and cultivated energy crops that would not hamper food production could be at least 50.4 PJ annually in Finland. (Bioenergia ry 2020, 17; Tuohiniitty & Laurikka 2021.)

The potential of unutilised straw from agricultural side streams is assumed to be 18 PJ per year, calculated on the assumption that 50% of agricultural straw could be used without harming food production and soil condition. Of this, 45% could be used for energy production and 5% for use in animal bedding. Straw has also been considered for use as a feedstock for bio-oil and second-generation bioethanol. It would also be possible to digest the agrobiomass into biogas. It have been estimated that the theoretical biogas production potential from Finnish manure to be 14.2 PJ (3.93 TWh) and the techno-economic potential to be 6.48 PJ (1.8 TWh). Agrobiomass could also be used for the production of so-called agri-pellets, for which suitable raw materials could include straw, rapeseed and oilseed rape stalks and cereal residues. The annual potential from grasses and other biomass is estimated to be around 22 PJ. For example, reed canary grass harvested in the spring is used as a mixed fuel for heating plants, while that harvested in the autumn is used for biogas production. In the exiting peatland, reed canary grass could be cultivated to produce an estimated 0.7 PJ (0.2 TWh) of biomethane per year by 2034, rising to around 1 PJ (0.3 TWh) by 2045. 10-20% of the exiting peat area would be suitable for short-rotation cultivation. (Bioenergia ry 2020, 17-18; Tuohiniitty & Laurikka 2021.)

Short-rotation trees are also potential resources, which include for example hybrid oak and silver birch. Growing hickory birch on exiting peatlands with a 20-30 year rotation has also been attractive and competitive if costs remain at 20 €/MWh. Willow cultivation has been studied in Finland since the energy crisis of the 1970s, with an estimated potential in southern Finland of 20-45 MWh/ha per year when using refined species and fertilisation. Willow plantations would be renewed every 20-25 years. (Bioenergia ry 2020, 19.)

The MISA project assessed Finland's potential for reforestation. The potential for reforestation is estimated at around 140 000 hectares of grassland in Finland in the early 2020s. It is assumed that about 3000 hectares of abandoned arable land and exiting peatland will be released each year, which would mean about 100 000 hectares of both by 2050. However, a more realistic estimate, according to Bioenergia ry, would be 30 000 hectares of reforested land by 2050. (Bioenergia ry 2020, 19.)

Recycling of biowaste in Finland still has room for improvement. Biowaste can be used, for example, to produce biogas. In 2021, most of the biogas produced came from biowaste and sewage sludge. In 2020, the Finnish Environment Institute (Syke) published monitoring data showing that the recycling rate of household biowaste is not increasing fast enough to meet EU targets. In 2020, Finland's recycling rate was 42%, compared to an EU average of 48%. The EU target is to reach a recycling rate of 55% by 2025 and 65% by 2035. Finland needs incentives to meet EU targets. In France, for example, there is an incentive-based pricing system and waste management charges are based on the weight of the waste. (Vanhamäki & Vinkka 2022; Kaariaho & Pirtonen 2022.) The EU Commission has proposed additional charges on waste going to incineration as an economic incentive and a ban on the construction of new waste incineration plants (YM 2023c). In 2020, around 44 000 tonnes of biowaste were sorted in the Finnish metropolitan area, which HSY used to produce 20 000 MWh of renewable heat and electricity. It is estimated that if people in the Helsinki metropolitan area alone sorted their biowaste, 150 000 tonnes of soil and 60 000 MWh of renewable energy could be produced annually. (STT 2021; STT 2020.)

The impact of carbon capture in energy production has also been discussed. The new Finnish government's programme also includes mentions of promoting technical carbon sinks. Finland could have one of the best conditions to be carbon negative and to produce carbon negative products with biomass. Bioenergy-related carbon capture methods are BECCU, where the captured carbon dioxide is utilised elsewhere, and BECCS, where the captured carbon dioxide is stored. It is currently being discussed that wood raw materials should be directed to material production rather than used in energy production, thus giving wood a better value. However, it has been suggested that in the future it might be possible that the tonnes of carbon dioxide captured might have enough value to make it more profitable to use biomass for energy production rather than biomaterials. The profitability of carbon capture technologies is still a challenge that would require subsidies, for example by rewarding carbon-negative production. The IEA estimated a few years ago that the emission allowance price would have to exceed \$65-76/tCO_2 for carbon capture to be profitable in a biomass plant, which was at least temporarily exceeded in 2022. It has been estimated that the introduction of carbon dioxide capture technologies could achieve a reduction of 9 Mt by 2050, a reduction of more than 90% compared to 1990 emission levels. (Tuohiniitty & Laurikka 2021; Bioenergia ry 2020, 6, 12, 33, 35; Hyppönen & al. 2022, 24; Koljonen & al. 2022, 31.)

In Finland, hydrogen is seen as playing a major role, especially as a raw material for industry and in heavy transport that is difficult to electrify. 88% of the hydrogen produced in Finland is used in the production of oil and biofuels (Valtioneuvosto 2023a, 9). Thus, clean hydrogen as a feedstock is also linked to biofuels. Hydrogen can also be produced from biomass in processes such as SMR, gasification and pyrolysis. However, the purity of hydrogen from the product gas from biomass gasification, for example, is quite poor compared to hydrogen from electrolysis of water. On the other hand, the cost of electrolysis is higher due to high electricity consumption. (Motiva 2023b.) According to a study published by the government in May 2022, low-emission hydrogen production would be 3.7-7.8 TWh by 2030 and 6.4-132.9 TWh by 2050 based on five different scenarios, some of which had significant exports of hydrogen and electro fuels. The National Hydrogen Strategy sets a target for hydrogen production by electrolysis of at least 0.2 GW capacity by 2025 and 1 GW capacity by 2030. The primary aim is to develop the value of the domestic hydrogen supply chain and, secondarily, the export potential. (IEA 2023b, 33.)

Biomass production from algae in Finland is still in the research phase, which poses technical challenges in terms of economic viability. Algae have good carbon sequestration potential, which is helpful against climate change. Business Finland is funding the ROBA (*Robust Algae Systems*) project that aims to create economically viable processes for algae cultivation. For example, Neste, which is involved in the project, aims to expand its range of renewable feedstocks and microalgae is one potential option for oil production. So far, there are no major projects in Finland in the near future for algae. (Salmi & Toivari 2022.)

To meet climate targets, the use of bioenergy is unlikely to decline, at least not in the near term. Bioenergy has so far been the most widely used renewable energy source in Finland as a replacement for fossil fuels and therefore expected to remain an important replacement for district and industrial heating in the coming decades. (IEA 2023b, 98; Hyppönen & al. 2022, 47-48.)

6.1 Future energy system of Finland: towards a carbon neutral 2035

Excluding emissions from the LULUCF sector, the energy sector accounts for almost 80% of Finland's total greenhouse gas emissions. Therefore, the energy sector is essential for reducing emissions. As part of Finland's climate and energy strategy, calculations of the energy system and greenhouse gas emissions have been made based on the WEM (*With Existing Measures)* and WAM (*With Additional Measures*) scenarios. The WAM scenario includes additional measures to achieve carbon neutrality by 2035 and to carbon negativity thereafter. In turn, the WEM scenario follows the WAM scenario of the previous energy and climate strategy, which measures have already been implemented. In this case, those implemented before 1 January 2020 are included in the WEM scenario. Scenario WAM-H is a modified version of the WAM scenario, considering the decisions of the September 2021 government budget negotiations, KAISU (*Medium-term Climate Policy Plan*) draft actions and their refinements. The main difference relates to the setting of greenhouse gas emission targets, which are not set in the WAM-H scenario but are driven by climate and energy policies. (Koljonen & al. 2022, 6, 9, 11, 16.)

According to the WEM scenario, primary energy consumption in 2035 could reach 1500 PJ at most, after which begins a gradual decline. The WAM-H scenario is about 2% lower, because of the increase in energy efficiency. Figure 19 shows the WEM and WAM-H scenarios for primary energy consumption up to 2050 by energy source. (Koljonen & al. 2022, 16.)

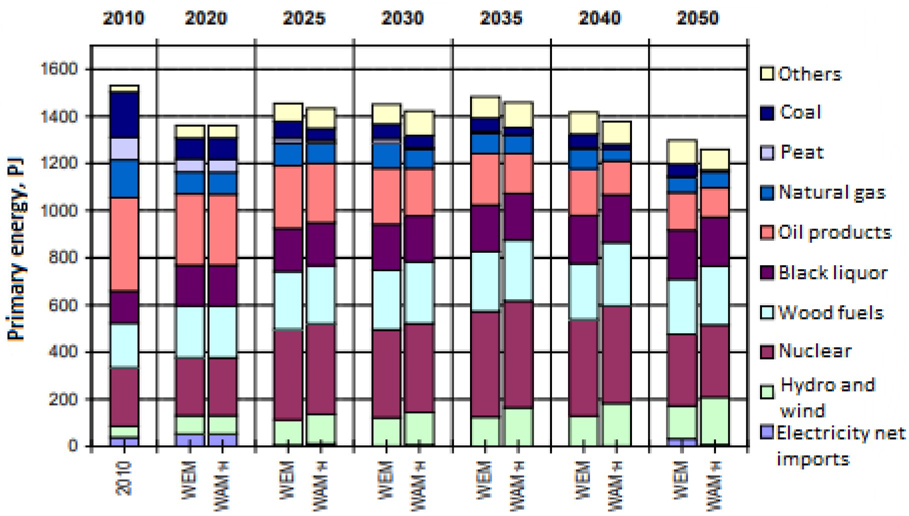

Figure 19. WEM and WAM-H scenarios to 2050 by energy source (Koljonen & al. 2022, 16).

In 2019, the share of fossil fuels was around 42%. Fossil fuel use in primary energy consumption is projected to decline to around 30% in 2030, 25% in 2040 and 20% in 2050 in the WEM scenario. In the WAM-H scenario, the reduction is steeper due to the stricter measures it takes into account. The use of coal and peat will decline steeply, especially peat very soon by 2025 in both scenarios. The use of natural gas and oil will also decrease, but more slowly. The transport and industry sectors may be the most challenging sectors to become fossil-free. To achieve carbon neutrality in 2035 and negativity thereafter, Finland must rely on increasing natural and technical carbon sinks. The WAM scenario aims to strengthen net sinks by 3 MtCO2 by 2035 compared to the WEM scenario. (Koljonen & al. 2022, 10, 16-17.)

In both scenarios, fossil-free energy increases accordingly to replace the fossil fuels that are being phased out. Nuclear power, wood-based fuels, hydro and wind power are the main contributors. In the WEM scenario, the share of renewable energy is assumed to be around 700 PJ in 2035 and around 730 PJ in 2050, compared to around 760 PJ in 2035 and around 840 PJ in 2050 in the WAM scenario. Relatively the strongest growth in renewables is expected to come from wind power in the coming years. Solar power is also expected to show more growth later in the 2030-2040s. In addition, the share of woody biomass is also expected to increase, mainly as a replacement for coal and peat. The growth in woody biomass is largely due to by-product flows from forest industry production and the growth of raw wood. Figure 20 shows the growth of wood fuel consumption from 2005 to 2050. (Koljonen & al. 2022, 16-18.)

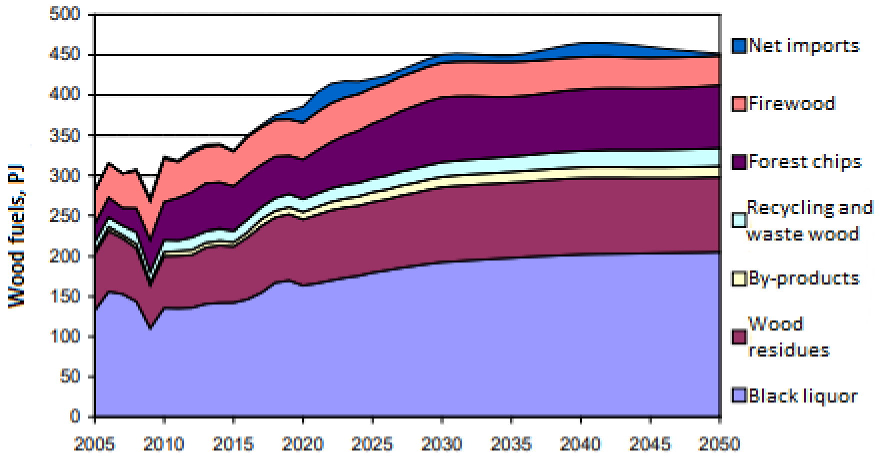

Figure 20. Wood fuel consumption from 2005 to 2050 in the WAM-H scenario (Koljonen & al. 2022, 18).

In 2020, almost 420 PJ of bioenergy was used, of which wood energy accounted for 80%. Wood-based energy is estimated to grow to 450-470 PJ by 2035 and then remain at that level. Bioenergy is projected to grow to 500-518 PJ by 2035. The rest of the growth comes from agrobiomass, biowaste and imported biomass. Importing wood could potentially increase wood fuel supply, but for sustainability reasons it is capped at 18 PJ, compared to

14 PJ imported in 2020. Although the amount of bioenergy would remain at least the same, its relative share of renewable energy would decrease. Especially in electricity generation due to growth of wind and solar power. In 2035, bioenergy is expected to account for 60% of renewables, while nowadays bioenergy accounts for more than 80% of renewable energy. (Koljonen & al. 2022, 18; Hyppönen & al. 2022, 47-48.)

6.2 Finland's fossil-free energy system and biomass

A fossil-free energy system would be the most ambitious system against climate change and also improve the energy self-sufficiency of Finland, although it would require a lot of new infrastructure, investments, and construction. According to a study commissioned by the Geological Survey of Finland, if the fossil fuels in the Finnish energy mix were directly replaced, this would require an increase of about 500 PJ fossil-free energy. The research team created six different fossil-free scenarios that could theoretically replace the current Finnish energy system, which can be used as a helpful tool for the real transition, although in reality the transition will be gradual. (Michaux & al. 2022, 6.)

In all scenarios, it was essential to focus on to reduce the demand for energy and resources. The sustainable volume of annual harvesting was estimated at 80.5 Mm^3 according to the Natural Resources Institute of Finland. Scenario 1 focused on full electrification, where all new energy production and light transport would be electrified. Scenario 2 was weighted towards a theoretical maximum amount of biomass, where all biomass going to industry would also be used as energy. Scenario 3 was a hybrid model using electricity and biomass in different sectors, while scenario 4 was a hybrid model including ground source heat pumps for heating. Scenario 5 presented an option not to increase electricity generation capacity but still phases out all fossil fuels. However, that would require demand for electricity consumption to halve. In the last scenario 6, energy consumption is assumed to be halved and geothermal heat pumps are used for heating at the building scale and biomass CHP plants at the industrial scale. (Michaux & al. 2022, 8, 61-91; Luke 2023c.)

One of the major tasks of the study was the conversion of transport to fossil-free, because it is not possible to electrify everything, so support from hydrogen and biofuels has to be sought. In addition, the production of heat for industrial and domestic use was also an essential issue. Electrification also requires a lot of extra production capacity to replace both fossil electricity and imports. For example, in scenarios 1, 3 and 4, additional annual production capacity of 120-150 TWh would be needed. In 2019, electricity consumption was around 86 TWh. Such a large capacity increase would require a lot of upgrading of Finland's existing electrical grid. Additional renewable electricity production was assumed to be generated by wind power in the scenarios. (Michaux & al. 2022, 6, 61-91.)

Energy storages play an important role in an energy system based on highly variable renewable energy to provide flexibility when electricity production and consumption are not in balance. Security of supply and service are societal objectives that must be ensured, which also partly increases system costs. For this reason, cost-effective solutions need to be found. In the scenarios used in the study, additional wind power is suggested to be stored in battery banks. Battery technologies have advanced, but there is still room for improvement on a larger scale. Other possible solutions could include hydro storage, if a suitable location can be found, and hydrogen as an energy carrier. Hydrogen could be produced from renewable electricity by water electrolysis and later used in fuel cells or gas turbines to generate heat and electricity. (Michaux & al. 2022, 61-91; Prabhansu & al. 2022, 401.)

In the study, hydrogen played the biggest role in maritime transport and heavy road transport. Biofuels, in turn, played a role in aviation transport. In principle, these could be electrified, but for now it is seen as too challenging to implement, as such major investments would be needed to be competitive. For aviation, biofuels are seen as the best solution for now as hydrogen would still need further development in areas such as storage and safety. Hydrogen and biomass as energy carriers are both capable of being stored, thus allowing flexible use at the desired time. The advantage of hydrogen over biomass is that it could be produced in relatively unlimited quantities from other renewables when there is a limited amount of biomass available. However, biofuels already have mature commercial and well-known technologies and infrastructures in place, making it already a competitive alternative. In all scenarios of the study, even in scenario 2, which tries to rely entirely on biomass, it is noted that there is not enough biomass available to be a sufficient solution on its own, even though Finland has a relatively high availability of biomass, especially woody biomass, compared to other countries. (Michaux & al. 2022, 61-91.)

In five of the six scenarios, the share of biomass in energy production was increased at the expense of the forest industry. The use of wood in the forest industry is not declining, as processed wood has more commercial value and is therefore more economically viable for wood use. It has therefore been suggested that the use of roundwood for energy production should preferably be directed towards industry and that energy production should focus more on the use of forest residues (Hassinen 2021). In addition, as mentioned in previous chapters, the supply of wood has also been affected by the Russian war in Ukraine. Other biomass types are also unlikely to be of sufficient help in the near future. (Michaux & al. 2022, 61-91.)

Scenarios 1 and 2 of the study were mainly reference scenarios, representing the maximum demand for electricity and biomass. Scenarios 5 and 6 provide a good basis for reducing energy demand, but in reality it is unlikely to be halved in the short term. Hybrid scenarios 3 and 4 are perhaps the closest to feasibility, of which scenario 4 is possibly the most convincing, because in terms of security of supply and risk diversification, it makes sense to rely on several different production methods. Of course, there are uncertainties in this scenario too, as hydrogen and geothermal technologies still need further development to work cost-effectively on such a large scale. (Michaux & al. 2022, 6, 61-91.)

In scenario 4, biofuels were used to replace fossil fuels, especially for industrial heat production in CHP plants and aviation. Hydrogen was used to replace fossil fuels for shipping and heavy road transport, geothermal to replace district heating and residential heating, and the rest of the replaced energy demand was met by electricity. Such an increase in electricity generation from wind power alone would require a total of 36 GW of additional capacity. In June 2023, Finland had a total wind power capacity of around 6.1 GW and by 2025, about half more of this capacity will be installed (Suomen Tuulivoimayhdistys ry 2023). This would be a major task and would require a faster rate of construction per year than today if, for example, 36 GW of wind capacity were to be reached by 2035. The electrical grid also needs major upgrades and additional construction. It should also be considered whether it is physically possible to accommodate this much new wind power within Finland's borders. However, wind power, especially onshore is currently quite mature and cost-effective to build. (Michaux & al. 2022, 6, 61-91.)

Biomass can be seen as a good partial solution among other renewables, but perhaps not sufficient for a whole solution. However, biomass already plays an important role and will continue to remain strong. The problems are mainly related to the sustainable availability of biomass, which would need to be solved before bioenergy production could be greatly increased, as currently woody biomass harvesting is close to the sustainable limit (Luke 2023c).

6.2.1 Future of transport

Finland's target is to halve domestic transport emissions by 2030 compared to 2005 levels and to be completely emission-free by 2045, where electricity alone would probably not be enough. According to the study by AFRY, the share of electricity in passenger cars in 2050 is estimated to be around 82% and 18% for renewable fuels. For heavy road transport, the share of electricity is estimated at 12% and renewable fuels at 88%. No electricity is estimated to be used for marine and aviation transport, but renewable fuels are estimated at 55% and 63% respectively. Unlike the study by the Geological Survey of Finland, the AFRY study did not assess the contribution of hydrogen to the transport sector. (AFRY 2022, 4.)

Switching from a traditional internal combustion engine vehicle to an electric vehicle has mainly been done by switching to a new car. The share of electric cars in imported new and used vehicles has grown rapidly in recent years. However, Finland's car fleet is very slow to renew and the average age of car scrapping is 22 years. The car fleet has also become even more obsolete over the last ten years, so that even old internal combustion engine cars have not been replaced easily by newer ones. As a result, the energy efficiency of transport has not progressed as hoped, which is where electric cars could help. By the end of 2021, there were almost 100 000 electric cars on the road, of which around 23% were full electric cars and the rest hybrids, covering 3.6% of all passenger cars. (AFRY 2022, 4; Valtioneuvosto 2022, 97.)

By 2030, CO_2 emissions from new passenger cars should be on average 37.5% lower than in 2021, which may be increased to 55%. In March 2023, the European Council adopted a regulation requiring new cars and vans to be 100% CO_2-free by 2035 (European Council 2023). The EU's CO_2 limit legislation is pushing car manufacturers towards electric cars or possibly hydrogen cars as the technology develops, which is behind electric cars. In order to meet the EU's strict CO_2 limit legislation, Finland is also aiming for the wide adoption of electric vehicles. Electric vehicles are also expected to reduce final energy consumption in domestic transport by 30% by 2035 and by more than 50% by 2050 in the WAM-H scenario. (Valtioneuvosto 2022, 94-98; Koljonen & al. 2022, 25-26)

The 2030 emission reduction targets of halving them would make sense to be achieved through widespread electrification of cars, but the problem is the fact that the vehicle fleet has been slow to renew. Another help is the biofuel distribution obligation, which is set to rise to 34% by 2030. At the beginning of 2022, it was 19.5%. Biofuels are the only way to cut emissions from the current car fleet at the moment, but if the goal is to move away from fossil fuels completely, biofuels are unlikely to do so alone. (AFRY 2022, 4-5.)

Biofuels could be seen as playing a major role in helping electrification of passenger cars to begin. Although the price of electric cars has come down, they are still beyond the reach of most consumers. To get consumers to use electric cars, prices would have to come down significantly, which will take at least several more years. Furthermore, care should be taken to ensure that there is sufficient charging infrastructure for the growing fleet of electric cars. The harsh weather conditions in Finland can also be a contributing factor to uncertainty and the possible need for regular longer journeys, as distances in Finland are in some areas quite long. For this reason, electric hybrids could be quite attractive alternatives to the electric cars for Finns. It would even help if all regular shorter distances, such as commuting, could be driven using electricity and, preferably, the internal combustion engine of the hybrid could be fuelled by biofuels, when needed. Unfortunately, hybrid car prices are also quite high.

The uptake of electric and hybrid cars would require strong incentives. The purchase price of an electric car or electric hybrid is certainly one of the barriers to buy an electric car, if you can buy a much cheaper internal combustion engine car that is considered to be reliable. Finland used to have a 2000€ purchase subsidy which was ended in the beginning of 2023. In addition, subsidies of 2000-6000€ were available for the purchase of electric vans and 6000-50 000€ subsidies for heavy transport, valid until the end of 2024. Smaller subsidies were also awarded for converting an oil-fuelled vehicle to run on ethanol or gas also until 2023. Support has also been allocated to improve the infrastructure for electricity, hydrogen and biogas distribution. For example, €34 million has been reserved for improving electricity distribution infrastructure alone and the number of public fast chargers will be increased from 300 to 1400. Efforts are also being made to reduce the number of cars on the road. A total of around €50 million has been allocated to public transport development and transport behaviour change, such as carpooling. (IEA 2023b, 73-74.)

By targeting incentives in the right way, the desired results can be better achieved. In Finland, the incentives have not yet been sufficient, as annual sales of electric cars have not reached the annual targets for rejuvenating the car fleet. (Valtioneuvosto 2022, 97.) The removal of subsidies is likely to weaken purchasing decisions, along with the current economic uncertainty and rising interest rates. In other countries, such as Norway, Germany and Sweden, the purchase of electric cars has been stronger because of incentives. (Turunen 2022.) If Finland wants to continue to increase the share of electric and hybrid cars, support should be continued, at least in the current economic situation, until the desired level is reached. Fiscal measures in favour of electric and hybrid cars could also help. Otherwise, the targets set may not be achieved.

Heavy transport is unlikely to be electrified, at least not by 2030, leaving either biofuels or hydrogen as the only fossil-free alternatives. However, hydrogen technology is still so far behind that it is unlikely to become a more widespread fuel source until after 2035, by which time the targets should be already well underway. This would leave biofuels the only option if fossil fuels were not allowed to be used at all. But it seems rather unrealistic to expect that complete fossil-free status can be achieved in the next ten years or so. The same applies to maritime and aviation transport. One of the key issues is the sufficiency of biomass as a feedstock, which would be needed in large volumes. In April 2023, a proposal to extend ETS to maritime transport gradually from 2024 to 2026 were adopted in the 55 package. It also included new separate ETS for buildings, transport and fuels in other sectors, which will therefore affect heavy transport, where reducing emissions is challenging. (European Council 2023). Either hydrogen technology needs to develop faster or biofuels or blends need to be increased to meet the targets. Finland's railway transport, on the other hand, is already highly electrified and aims to be fully electrified by 2050 (IEA 2023b, 74).

The share of biogas in transport has been rising sharply since 2017. A total of 570 GWh (2 PJ) of new production is currently pending in Finland, over half of which is for heavy road transport as liquefied biogas and it is mainly produced from biowaste. (Suomen Biokaasu ja Biokerto ry 2023.) However, much more production would be needed for biogas to play a crucial role in meeting the 2030 targets. The potential for biogas production could be much higher. If agricultural biomass is considered, the production potential is estimated at 4 TWh. The potential of arable biomass has not been taken into account, but could well be several terawatt-hours (Suomen Biokaasu ja Biokerto ry 2021).

Electrification in avitation will be even further away than in other modes of transport. For this reason, biofuels would bring the greatest emissions savings when other transport is electrified as widely as possible. For example, Neste has a total sustainable aviation fuel production capacity of about 1.5 Mt at its refineries in Porvoo, Rotterdam and Singapore at the end of 2023. The total amount of sustainable aviation fuel to be refuelled in Finland is estimated to be around 1.125 Mt by 2030. (Traficom 2021, 68-70.) Finnair is aiming for carbon neutrality by 2045 and has purchased some sustainable aviation fuels from Neste, which can currently be blended up to 50% with fossil fuels (Neste 2023).

6.2.2 Future of heating and cooling

Biomass has played an important role in heat production already to this day and fossil fuels have been steadily replaced by solid biomass combustion and waste heat. Solid biomass combustion can be expected to continue, especially in the near future. In the longer term, though, Finland is aiming to move away from combustion technologies in heating. Heat pumps, waste heat and geothermal energy would be used instead. Finland has become one of the leading countries in heat pump sales and the development of heat storage solutions. This brings flexibility to the district heating network, as well as for variable electricity generation, where new technologies can integrate different sectors and, for example, allow excess electricity to be stored as heat or used in the district heating network. Another example of sector integration is the transfer of industrial process waste heat to the district heating network. (IEA 2023b, 12.) Finland has an extensive district heating network, which has made it quite possible to reduce the use of fossil fuels and thus reduce emissions compared to if everyone had their own heating system. Increasing system integration will also bring further opportunities to optimise energy production and consumption and bring help to a narrowed fuel mix, thus easing the growing demand for biomass.

Some non-combustion-based technologies are, though, only just becoming commercialised, meaning that wood fuels are very likely to be part of Finnish heating systems for at least the next two or three decades. Woody biomass imports from Russia have been high in the past, but the Russian war in Ukraine has reduced imports, resulting in the need to import missing woody biomass from other countries or to increase logging in domestic forests. In this case, the sustainability of forests could potentially be at risk and great attention should be paid to the implementation of sustainable forest management.

In addition to transport, biogas can also be used for heat and power generation, but it may make better to target biogas more towards the transport sector for now, where it has been more challenging to find alternative fuels. On the other hand, it should all be considered on a case-by-case basis. Agrobiomasses can also provide good feedstock sources to support woody biomasses. The potential of agricultural by-products is estimated at 50 PJ per year, which could cover more than a quarter of the current district heating fuel supply (Bioenergia ry 2020, 17). Non-renewables covered about 75 PJ in 2021 (IEA 2023b, 69). Agrobiomasses could therefore have good potential to help replace non-renewable energy sources.

6.2.3 Future of electricity

In electricity generation, biomass is probably going to be used in CHP plants as it is now. Possibly slightly increase when heat-only plants are converted to CHP plants, but no significant increase as other renewables grow, especially wind and later possibly solar replacing fossil fuels. If the share of other renewables in electricity generation develops substantially, then it might be more profitable to shift the use of biomass to other sectors. On the other hand, it is good that not all electricity generation is based on variable renewable energy sources or any other particular source.

Nuclear power and bio-CHP already work well as a base production. In 2021, the share of fossil-free electricity in Finland was 86%, in which case the current electricity demand could be met quite easily with fossil-free energy alone, simply by adding wind power combined with energy storage. However, electricity demand is expected to grow as electrification proceeds in different sectors, so wind power should increase quite massively. It is estimated that extensive electrification in Finland would increase electricity demand by more than a fifth by 2035 and by 2050 it would double from current levels to almost 170 TWh annually. Also, wind power storing is still an evolving area. The large-scale use of hydrogen could partly reduce the use of biomass and offer the possibility of storing electricity instead of batteries. However, the production of hydrogen by electrolysis from water is highly electricity consuming and would therefore increase electricity consumption by about 20 TWh by 2050. (Statistics Finland 2022c; Peljo & Koistinen 2021.) Electricity generation is likely to rely more on other fossil-free energy sources and biomass will be used in CHP plants. On the other hand, the total amount of electricity produced from biomass will increase as electricity produced from coal and peat is phased out and replaced by CHP production.

6.2.4 Future of industry

As mentioned earlier, the most energy-consuming sector of all is industry, with almost half of it consumed by the paper and pulp industry. In industrial process heat production, biofuels also play the largest role of renewables. However, more electrification is increasingly being implemented where it can be, what will be the main trends in the industry (Koljonen & al. 2022, 12). This will contribute to increase energy efficiency. Industry is very likely to grow in the future, so energy efficiency will have a compensating effect on energy consumption. At the same time, this also means an increase in industrial by-products, which can be used for energy production, as demonstrated earlier in figure 20.

There is also untapped waste heat recovery potential in industry, estimated at around 50 PJ, but there are still challenges in terms of economic viability, with the biggest costs coming from the construction of the transmission network and heat pumps (Valtioneuvosto 2022, 38). With advances in technology, such as heat pumps, it could be possible to exploit what was previously not available and could be used either in the industry's own process or elsewhere, for example in district heating.

The largest industrial emissions are from carbon steel production and fossil oil refining. In the production of carbon steel, the aim is to switch to the use of hydrogen produced from renewable sources, such as the electrolysis of water. The petrochemical industry also aims to switch to renewable feedstocks. (Koljonen & al. 2022, 12, 33.)

Industry is one of the most difficult sectors to reduce emissions. Fossil fuels could be replaced in industrial processes by increasing electrification and CHP processes that promote energy efficiency, biofuels and their by-products, and waste heat recovery from industrial processes. BECC systems integrated with biorefineries and forest industries could ideally help to achieve carbon negativity, which is the goal for Finland after 2035.

6.3 SWOT analysis

SWOT analysis means identifying internal features, including strengths and weaknesses, and external features, including opportunities and threats. The SWOT analysis in table 2 summarises the issues that could be considered when fossil fuels are replaced by biomass.

Table 2. SWOT analysis of replacing fossil fuels with biomass in Finland.

Strengths	Weaknesses
· Renewable energy source · Carbon neutral when used sustainably · Versatility of use · Relatively rich in woody biomass · Finnish expertise · Strong forest industry · Biomass already has a strong role in the Finnish energy system	· Requires additional investments · Lower energy density than fossil fuels · Variable biomass quality · Sustainable woody biomass growth potential in energy production quite limited
Replacing fossil fuels with biomass in Finland	
Opportunities	**Threats**
· Potential of other types of biomass · Hydrogen production from biomass · Recovery of by-products and waste · Versatile applications · Advanced products from biorefineries · Export potential · Additional job opportunities · Carbon negativity through CCS	· Competition for land use and biomass feedstock use · Sustainability concerns · Political decisions slow down biomass deployment · Forest disasters · Fossil fuels cannot be fully replaced

The strengths of biomass over fossil fuels include its renewability and carbon neutrality when it is used in a sustainable way. Biomass can also be used in a wide variety of ways in all sectors and also as a replacement for fossil fuels in feedstock materials. Finland is relatively rich in woody biomass in particular, compared to other EU countries, for example. Among the other EU countries, the situation in Sweden is similar to that in Finland for forest biomass. Domestic forest biomass contributes to the self-sufficiency of raw materials which fossil fuels do not provide. Furthermore, the strengths of Finland include a strong forest industry and expertise in biomass-related technologies and their development, which has been building up over the years. Biomass already has played a strong role in the Finnish energy system, especially in industry and heat production. It has also played an important role in reducing the use of fossil fuels and emissions to this day and notably in the near future.

The weaknesses of replacing fossil fuels with biomass are the additional investments needed to convert old infrastructure and systems to run on biofuels. This includes, for example, transport, handling and storage, as well as the conversion of production plants to be suitable for biomass. The quality of biomass can also vary widely and the energy density is typically lower compared to fossil fuels, due to the more diverse chemical composition and moisture content of biomass, among others. The growth potential of sustainable woody biomass for energy production can also be quite limited, which can lead to over-exploitation of forests.

Opportunities to increase the use of biomass could be found in the use of other types of biomass, such as agrobiomass, short-rotation energy crops and algae. It is thought that there is a lot of untapped potential in agrobiomasses, which could be increased quite quickly, as well as short-rotation crops. In turn, algae could be used to produce oil for biofuel production, though algae technology still needs to be developed for Finnish conditions, but the potential is there. The hydrogen needed in the future could, if necessary, also be technologically possible to be produced from biomass or obtained as a by-product from biomass refining processes. Improved utilisation of by-products and waste will contribute to Finland's circular economy target 2035. As recycling becomes more efficient, the amount of waste is also reduced. For example, by digesting biowaste, biogas can be produced, which can be used as a fuel for transport or to produce heat and electricity.

Other opportunities are that biomass can be used in many different applications and as a weather-independent backup source. Finland has expertise in biorefineries, where biomass can be processed into more valuable bioproducts and biofuels. For example, the fuel properties of forest industry residues can be improved by pelletising the material to make it more energy-dense or by torrefaction to give the biomass coal-like properties. More refined products, such as synthetic and advanced biofuels, may be the export products of the future as other countries increase their demand for biofuels. These also provide an opportunity for increased domestic jobs. Carbon dioxide capture technology will also be increasingly invested in. Carbon capture combined with bioprocesses can even aim for carbon neutrality and produce carbon negative products, where Finland could be a world leader.

Threats to biomass use may include competition for land use and also competition for feedstock materials. Biomass, especially wood-based biomass, is used not only for energy production but also as a raw material for forest industry for bioproducts. In turn, energy crops may compete for land use with food crops or agrobiomasses with animal bedding and feed production. Unsustainable land use in the LULUCF sector can also be a threat if sustainable practices are not followed, which, in the worst case, can lead to deforestation and forest loss. Some policy decisions can also pose a threat to biomass use. For example, Finland needs to be prepared for the possibility that EU Member States may be required to tighten up their use of biomass in energy production. Similarly, the temporary loosening of biofuel distribution obligations decided in Finland could slow down the shift away from fossil fuels in transport. In addition, there is a risk that fossil fuels will not be phased out as quickly as is the aim, because the challenge of replacement is so great. For this reason, it is important to create a system in Finland based on a variety of different energy sources, for which developing technologies will offer opportunities.

7 Conclusions

Finland's energy system has long relied on fossil fuels, but they are going to be phased out in order for Finland to meet its carbon neutrality target in 2035. Among renewable fuels, wood fuels are the most used energy source of all, but other renewables, such as wind power, tend to increase their share, especially in electricity generation. Reliability, balance between production and consumption, environmental friendliness and cost-effectiveness are the main factors to be considered for a new renewable-based energy system.

Replacing fossil fuels with fully renewable energy sources in every sector will be a major challenge, but not entirely impossible. Biomass, mostly wood-based, has so far played the biggest role as a replacement for fossil fuels, especially in industry and heat production. The share of woody biomass in district heat production has been increasing over the last decade and has been the main alternative to fossil fuels as other renewable alternatives still make up their share. In the industrial sector, biomass has also had the largest share, partly explained by the paper and pulp industry accounting for almost half of industrial energy consumption. However, industry still uses a lot of fossil fuels for process heat and material production.

Finland's electricity production is in turn quite diverse in terms of non-fossil energy sources. Nuclear, hydropower and wood fuels have been steadily contributing to carbon-neutral electricity generation for a long time. In the beginning of the millennium, in some years fossil fuels may have been the most used fuel, but over the last decade, their share has declined significantly, while wind power, for example, has started its rise. Electricity production has remained fairly stable, but much more production will be needed as demand for electricity will grow due to increasing electrification, which would also help to improve the energy efficiency of different sectors.

In the transport sector, fossil fuels still dominate. Finland's slowly renewing car fleet poses an extra challenge, because renewing the car fleet is only possible way to increase the share of electric or hybrid vehicles in traffic. Electric or hybrid cars would probably be the quickest solution to a large-scale phase-out of fossil fuels in passenger cars, but better incentives for buying electric and hybrid cars would be needed. Lower prices, subsidised purchasing, fiscal benefits and sufficient charging infrastructure have so far been the most effective solutions in other countries. On the other hand, biofuels could already help to some extent, as biofuel blends could already be used in existing vehicles or with minor modifications. However, biomass alone would not be sufficient as a solution on such a large scale replacement, since it is needed so widely elsewhere. Biogas, in turn, could be expected to provide a solution for heavy road transport as long as hydrogen still remains on the horizon. There could be additional biogas production potential in biowaste and agrobiomasses, but production should be increased significantly. The same applies to maritime and aviation transport, but biofuels would also be very much needed. The target for railway transport is to be fully electrified by 2050.

The biggest challenges to achieving a carbon-neutral Finland by 2035 are likely to be in reducing fossil fuels from the industrial and transport sectors. Energy consumption is highest in industry and will continue to grow. In transport, finding alternative fuels to replace fossil fuels is the most challenging. To make transport completely fossil-free, the number of electric and hybrid cars should increase faster, hydrogen technology should develop quicker or biomass should be made sufficient by finding new potential biomass feedstock potentials. Improving energy efficiency can also help, which is also expected to stabilise the growth in energy consumption in industry. For industry, fossil-free and energy efficiency could possibly be best achieved by improving energy efficiency through electrification and CHP plants and replacing fossil fuels by increasing the share of biomass and waste heat.

Fossil-free heat production is likely to be best achieved by further increases in biomass. Woody biomass will be increased mostly through forest industry by-products and residues. In addition, the potential of agrobiomasses and short-rotation energy crops could be great help to replace fossil fuels, as their production could be deployed quite rapidly. It could be possible to cover at least more than half of the fossil fuels used for district heating by utilising agricultural by-products. Later in the future, more extensive use of waste heat, a significant increase in heat pumps and the use of geothermal heat can be expected.

In Finland, 86% of electricity generation is already fossil-free. However, electricity generation needs to be prepared for increasing electricity demand due to electrification targets. Biomass, through CHP plants, has been a viable replacement for fossil fuels and will remain so and perhaps grow slightly, but other renewables are likely to make more significant growth in the future, such as wind and solar power. Varying renewable energy sources will also increase the importance of energy storages. Hydrogen could be an alternative in the future as the technology develops.

The strengths of biomass as a replacement for fossil fuels include, in particular, its renewable nature, its low emissions when used sustainably, and Finland's expertise and strong forest industry. The weaknesses of biomass are mainly related to its rather limited growth potential in the forest sector, the additional investments required for the changes and the quality weaknesses of biomass compared to fossil fuels. The opportunities for biomass are the untapped potential of other non-wood biomass feedstocks, the production of hydrogen from biomass and the possibility for Finland to be a leading country in terms of expertise and technology, acting also as an exporter. Threats to biomass include competition for land use and feedstock, risks to the sustainability of biomass use, and policy decisions that would pose challenges to the use of biomass for energy production.

Finland has high carbon neutrality targets, but it is possible that with current policies phasing out fossil fuels will not be fully achieved in all energy sectors. In this case, carbon capture combined with bioprocesses could play a major role and enable the targets to still be met. However, carbon capture is still a relatively expensive and emerging technology, so it should not yet be relied on heavily.

While the contribution of biomass as a replacement for fossil fuels in different sectors is not sufficient to be the only solution, it has an important role to play in the energy system to complement where other renewables are lacking, now and certainly in the near future. On the other hand, it is also good that the energy system does not depend too much on a particular energy source, which helps the system to manage different situations and seasonal variations. However, the main problems for increasing the use of biomass are related to the limited availability of forest biomass, as EU countries, among others, will also increase their use of biomass to meet climate targets. Thus, further research could be of interest to identify more precisely the potential of other types of biomasses than woody biomass.

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