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Growth by integrating bioeconomy and low-carbon economy

Scenarios for Finland until 2050

VTT

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LIST OF SYMBOLS

adt	Air dry ton
AGE	Applied general equilibrium
billion	1000 million, 10^9
Bio-CCS	Bioenergy with Carbon capture and storage
Bio-CCU	Utilisation of biogenic CO_2
BioEco	Bioeconomy scenario
BTL	Biomass-to-liquid
CAES	Compressed air energy storage
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CH4	Methane
CHP	Combined heat and power, Co-generation of heat and power
CNS	Carbon Neutral Scenario
CO_2	Carbon Dioxide
DAC	Direct air capture
EJ	Exajoule, 10^{18} joules
ETS	Emission Trading Scheme
ETSAP	Energy Technology System Analysis Programme
EU	European Union
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse gas
HTL	Hydrothermal Liquefaction
ICT	Information and communication technology
IEA	International Energy Agency of the OECD
kt	Kilotonne, 10^3 t
LULUCF	Land Use, Land Use Change and Forestry
Mt	Megatonne, 10^6 t
OECD	Organisation for Economic Co-operation and Development
P2G	Power-to-Gas
PJ	Petajoule, 10^{15} joules
PTF	Power-to-Fuel
PV	Photovoltaic
R&D	Research and development
RSOFC	Reversible solid oxide fuel cell
SNG	Synthetic natural gas
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
toe	Tonne of oil equivalent
TWh	Terawatt hour, 10^{12} watt hours
VA	Value added
VRE	Variable renewable energy
VTT	VTT Technical Research Centre of Finland Ltd

CONTENT

1. Foreword

Bioeconomy refers to the various sectors of primary production, such us agriculture, forests and fisheries, and industrial sectors, which transform bio-resources to bio-products. Industrial sectors in bioeconomy cover food and feed industries, cellulose, paper and wood processing industries, bio-refineries, chemical and energy industries, and also the marine and maritime sectors. In addition, bioeconomy includes ecosystem services of nature, such as recreation and wellbeing as well as tourism. In the European Union, bioeconomy has an annual turnover of above 2.2 trillion Euros and employs more than 18 million people[1]. In Finland, the annual turnover is nearly 50 billion Euros and employs 200,000 people correspondingly. At both the EU level and in Finland, the annual turnover has been slightly increasing since 2009 while the employment numbers have been slightly decreasing. However, the bioeconomy in Finland is rather different from the European average, where the agricultural sector and food industries account for 75% of the total bioeconomy turnover and forestry and forest industries cover 15% of the turnover, respectively. In Finland, the corresponding numbers are 30% and 63%, illustrating the greater importance of the forest sector in Finland's bioeconomy turnover compared with the EU level. However, even in Finland, agriculture and food industries employ nearly 60% of people working in the bioeconomy sector.

Bioeconomy is not important only because of its potential to contribute to Finland's welfare, but also to replace fossil fuels in energy production, transport and chemical industries. Bioenergy accounts already today for about 26%[2] of Finland's total energy consumption and the use of bioenergy and biofuels is expected to increase in the coming years due to national and EU-level policies and strategies in energy and climate change mitigation. On the other hand, to fulfil sustainability criteria in bioeconomy, we need to carefully optimize the use of natural resources in the most efficient way both in terms of material efficiency and value added. To ensure sustainable use of biomass resources we should also keep in-mind long-term and indirect impacts on the environment, climate, and welfare, like the impacts on natural ecosystems, carbon sinks in forests, and even global food prices.

In this report, the primary focus is to analyse how to achieve full bioeconomy potential and bridge the on-going research to industrial implementation. In the analysis, we have mainly focused on forestry and forest industries, agriculture and food industries, as well as on bioenergy and biofuels. The aim has been to illustrate effective bioeconomy pathways and the impacts of accelerated R&D and related investments in bioeconomy on Finland's welfare and greenhouse gas mitigation. The analysis is based on views and synthesis of a large group of VTT's experts in the fields of forest and food industries, biomaterials, clean energy, and scenario modelling. The synthesis and implications are drawn by using narrative scenario approaches and quantitative scenario modelling of future energy and industrial systems, national economy, and greenhouse gas mitigation[3] to study alternative future pathways towards a sustainable low-carbon society in 2050 and the role of

bioeconomy in Finland's economy and welfare. In the scenarios, research and development on sustainable products and materials, as well as clean technologies and related systems, have been combined in a systematic way. The objective of the work has been to give 'food for thought' based on numerical information that could be used for developing future bioeconomy strategies and evaluation of Finland's opportunities and challenges within bioeconomy. Thus, it should be noticed that there are several critical questions that are not discussed in this report requiring further analysis. Especially, the sustainable supply of biomass for the production of food and feed, materials, fuels and energy are of major concern and it may be expected that new policies and regulations will limit the use of certain raw materials for non-food uses, both related to wood and agrobiomasses. Secondly, the markets of new bio-based products are just emerging and the important question is how Finland will be able to put forward needed investments and bring new products into global markets.

In 2012, VTT published the report "Low Carbon Finland 2050", which included alternative scenarios for Finland to mitigate greenhouse gas emissions by at least 80% compared to 1990 emissions by 2050. Like the present study, the earlier work was based on research and knowledge of a large group of VTT's experts. The use of VTT's knowledge and analysis on Finland's opportunities to reach the low-carbon targets became very important as the Government of Finland established a Parliamentary Committee on Energy and Climate Issues in summer 2013 with the task of preparing strategic guidelines for Finland in order to achieve a low-carbon society. The central supporting research and analysis work for the Energy and Climate Roadmap 2050 preparation was a scenario work, which was initiated by VTT's low-carbon report, but this time carried out by the Tekes-funded multidisciplinary research project Low Carbon Finland 2050 platform (LCFinPlat)[4]. Since the publication of the above low-carbon scenario assessments, many market-related, policy and technological developments have changed these paths towards a sustainable low-carbon society. Thus, the analysis of this report takes into account the most recent information on Finland's and the EU's energy and climate targets, e.g. the policy framework and strategies up to 2030, as well as new knowledge on investments, costs, and innovations.

The report is based on two alternative low-carbon scenarios, which are compared with a Baseline[5] scenario. The first low-carbon scenario, referred to as CNS[6], focuses on Clean-Tech, e.g. implementation of smart and clean energy technologies. In this scenario, biomass is mostly used for the same industrial products as assessed in the Baseline but increased demands of advanced biofuels, and bioenergy. The other low-carbon scenario, referred to as BioEco[7], calls for radical innovations and new value-added products from biomass. As biomass is used less in the energy sector in the BioEco scenario, other renewables need to be brought to the markets to achieve the low-carbon emission target. None of the scenarios is expected to be literally realized but by comparing alternative pathways, certain conclusions may be drawn about future opportunities and steps forward.

2. Executive summary – Energy and climate objectives can be met while increasing welfare

Objectives of this work

The Strategic Programme of the Government[8] states a ten-year objective: "Finland is a pioneer in the bioeconomy, a circular economy and cleantech. By developing, introducing and exporting sustainable solutions we have improved the balance of current accounts, increased our self-sufficiency, created new jobs, and achieved our climate objectives and a good ecological status for the Baltic Sea".

The ultimate goal of this scenario analysis with integrated bioeconomy and low-carbon scenarios is to provide a better understanding of the present and to explore the future. The particular objective is to provide insight with the help of quantitative scenario modelling of future possibilities in fostering the growth of the Finnish economy with development of new bio-based products and clean energy technologies and, at the same time, to meet the low-carbon mitigation targets by 2050. In this report, we have mainly concentrated on opportunities for renewal of forest and food industries to produce more value-added products while the other bioeconomy sectors are included in quantitative analysis but not discussed in detail.

KEY MESSAGES:

- The present scenario work, strengthened by in-depth analysis on bioeconomy, is the first systematic, cross-sectoral analysis of the trade-offs and synergies of Finland's future bioeconomy and transition to low-carbon economy by 2050. Three scenarios were quantified to study the impacts on Finland's energy and national economies with energy system and macro-economic models. Even though the primary focus was on Finland's low carbon and bioeconomies, the scenario modelling also covered neighbouring countries and the whole EU, thanks to common energy and climate policies, transmission infrastructures, and commodity markets.

- One scenario represents the Baseline scenario, including thus Finland's and the EU's energy and climate targets up to 2030. The other two scenarios are so called "low-carbon scenarios", where global climate change is mitigated below 2 degrees C, meaning that the EU and other industrialized countries reduce their greenhouse gas (GHG) emissions at least 80% compared to 1990 emissions by 2050. The low-carbon scenarios are referred to as Carbon Neutral Scenario (CNS) and BioEco, of which the CNS scenario may use the biomass resources extensively for energy, while in the BioEco scenario biomass is primarily used for high-value products and energy use is constrained by assumptions on strict sustainability criteria, mostly to secondary residues. In the CNS, the ambition for GHG mitigation in Nordic countries is even higher than in the EU on average.

- The BioEco scenario shows that the **acceleration of the development of Finland's bioeconomy and cleantech makes it possible to reach both the ambitious greenhouse mitigation targets and increase Finland's economic growth by producing and exporting value-added bioproducts, clean technologies, and related services**.

- While graphic paper production is declining, new investments are currently being made in Finland, mostly to increase the softwood pulp production for hygiene and packaging. Even though a strong increase in wood-consumption is expected, there will be moderate impacts on the economy due to the decline in productivity of wood-based industries. This calls for development of new high-value-added bioproducts, which can also facilitate industrial renewal and creation of new business ecosystems. In the BioEco scenario, added value could be even doubled from the current amount of about 14 billion to nearby 30 billion in 2050 by putting the efforts into, e.g. upgrading value from mechanical wood products, pulp and paper, bio-based chemicals, and other industries utilizing wood as a raw material. However, market demand and economic feasibility of production are prerequisites for this.

- In order to secure climate change mitigation, sustainable use of biomass resources needs to be ensured. This leads to a need to direct biomass uses towards sustainable products having longer lifetimes in comparison to energy carriers, which is emphasized in the BioEco scenario, where the amount of small wood use to energy and biofuels is reduced to 1 million m^3, while it is close to 8 million m^3 in the CNS scenario. The total supply of domestic stemwood increases from the current amount of above 63 million m^3 to about 82 million m^3 in the CNS scenario, and to about 80 million m^3 in the BioEco scenario by 2050. However, in the BioEco scenario the considerably larger need for industrial pulpwood for bio-materials leads to an increase of wood imports from the current 10 million m^3 to nearby 15 million m^3 in 2050, which needs to be imported from sustainably managed forest as well.

- In Finland's agricultural sector, the current cost competitiveness in primary production is rather low and the profitability of the sector is expected to weaken even further with the current trend. Likewise in the forest industries, the existing focus of agriculture and food industries on unprocessed raw materials and semi-finished products as the core of exports should be transitioned towards high-value-added goods, thus increasing cost competitiveness. In the BioEco scenario the value added increased from the current approximately 6 billion up to 11 billion by advanced cultivation and by increasing the added value of agricultural products and thus food industries' annual turnover. However, also changes in human behaviour and acceptance of new protein sources are required for this development.

- The existing energy system in Finland is based on versatile energy sources, creating the opportunity for a resilient pathway to a low-carbon energy system. The shares of bioenergy and total renewable energy from total energy consumption were 26% and above 34% in 2016[9]. According to Finland's energy and climate strategy to 2030, the share of renewables should be increased to above 55% of the total energy consumption while coal should be phased out and the use of imported mineral oil should be halved. All these objectives are included in the Baseline scenario while the CNS and BioEco scenarios represent two alternative pathways up to 2050. In the CNS scenario, higher shares of bioenergy and advanced biofuels provide an opportunity for wider-scale utilization of carbon capture and storage (CCS) from these installations leading to higher cost-efficient emissions reduction potential than the average over the EU and about 90% GHG emission reduction in 2050 compared with the 1990 level. In the BioEco scenario, deep GHG reductions become somewhat more expensive in Finland than the average EU level due to assumed constraints for CCS investments and very strict sustainability criteria for bioenergy, but the total GHG reduction is nearly 80% in the BioEco scenario.

- The share of renewable electricity generation will increase close to 80% of the total electricity supply in both the CNS and BioEco scenarios by 2050. Even in the Baseline scenario with decided policies on targets up to 2030, the share of fossil electricity will be below 10% due to increased cost competitiveness of solar, wind and other renewable energy. In the CNS and BioEco scenarios, wind power production reaches 21–23 TWh in 2050, but also solar power could reach similar levels or even higher, if we assume that the cost of utility-scale solar power would decrease to 350 €/kW, meaning about 60% further cost reductions compared with the deep cost reductions experienced in 2010–2016. However, the total contribution of renewable energy from total primary energy supply is roughly at the same level in all three scenarios. While in the Baseline and CNS scenarios the supply of renewable energy remains highly on wood biomass, in the BioEco scenario it becomes more diversified. It is also noteworthy that in the BioEco scenario the electricity demand increases from the current approximately 80 TWh to 130 TWh due to strong electrification in 2050, while in both Baseline and CNS scenarios the demand is about 100 TWh. In the BioEco scenario, the electricity supply is also more dependent on electricity imports, which is 10% of the total supply, while in the CNS scenario only about 3% of electricity is imported.

- Electrification of the light-duty road transport is extensive in both CNS and BioEco scenarios and the contribution of hybrid and full electric vehicles gain a market share of 75–80%. In addition, fuel cell vehicles cover an additional 10–15% of the passenger car fleet. However, in the CNS the Finnish transport system is highly based on advanced liquid bio-fuels, while in the BioEco scenario even the light duty vehicles are highly electrified. It should be also noted that heavy duty, ship and air transport still need substantial amounts of liquid fuels, which could be advanced biofuels or synthetic fuels produced form renewable electricity via electrolysis to produce hydrogen, which could be either used directly in fuel cells or further converted into liquid hydrocarbons.

- All the scenarios assessed come to the conclusion that Finland's economy will grow but compared with the Baseline scenario, the CNS leads to about 0.6 percentage points loss in growth in 2050 while in the BioEco scenario, the growth is accelerated by more than 3 percentage points. In the CNS scenario, technology is focused on mitigation of greenhouse gases and the lower GDP growth reflects the rising relative prices of energy and materials. Therefore the contribution to GDP growth of all the other sectors, except construction and retailing, is slightly negative compared with the Baseline. In the BioEco scenario, the increase in growth compared with the Baseline mostly stems from the contribution of technology and production of new value-added products and thus generating growth from increased productivity and material efficiency. Unlike in the CNS, several sectors benefit from new bio-products from forest, wood products, and agro-food industries but the largest contributions are from wood product as well as pulp and paper industries. However, it should be noted that exports of Finnish clean solutions are not illustrated explicitly, which could change the picture of the CNS as well. Finland has a growing cleantech export business, including world-class knowledge on smart and clean industrial and energy systems and thus great potential for increased exports of clean solutions.

- The BioEco scenario leads to new types of industrial ecosystems, both in forestry and agriculture, enabled by digitalization and driven by a need for more tailor-made individualized bio-products, like food, furniture, or even textiles. On the other hand, reaching the 2050 climate goals requires transformation of the whole energy system towards flexible and intelligent systems with integration of distributed renewable energy resources, energy storages, smart transport and active consumers that also produce energy at their homes. The results indicate that we should on one hand focus on both cleantech and bioeconomy, ensure greenhouse gas mitigation to a safe level and, on the other hand, enhance sustainable and effective use of natural resources. It is evident that none of the scenarios will be realized as presented, and putting the efforts into both of the strategies we will be able to increase the welfare of the Finnish society and ensure sustainable development.

3. Introduction to bioeconomy transition

What do we mean by bioeconomy?

A low-carbon and resource-efficient society is a key for a sustainable economy and an overreaching goal to be reached by 2050. Bioeconomy can play a major role in reaching this goal, as recognized by the European Commission and its many Member States, including Finland. The concept of bioeconomy links together the sectors responsible for sustainable primary production, including agriculture, forestry, fisheries and aquaculture on one hand, and sectors producing final consumables, such as food, chemicals, materials and energy on the other. However, the long-term goal agreed to in Paris[10] of limiting the increase of global average temperature to well below two degrees will increase the demand for sustainable bioenergy and put more pressure on replacing the use of fossil fuels in producing chemicals and materials. At the same time the debate on sustainability and climate impacts of using biomass, especially for energy purposes but also for materials with a short life-cycle, is getting more and more attention within the science community and increasingly also in public discussions and in policy making[11,12,13].

The word bioeconomy has two parts, "bio" and "economy". "Bio" states that we are dealing with renewable resources, e.g. biomass in all forms. The latter part, "economy" states that we are focusing on operations, which generate economic actions by private consumers, companies, and other actors and which result in growth of the economy and thus society's wellbeing. It is of utmost importance that bioeconomy is sustainable from environmental, economic and societal points of view. According to European bioeconomy strategy, bioeconomy (or bio-based economy) "… encompasses the production of renewable resources and their conversion to food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnical, and energy industries"[14].

Finland's forests and forest-based sector play a central role in the economy. However, the global turmoil and declined demand for traditional paper products have fostered the renewal of the whole forest industry in Finland.

While paper production is declining, new investments are currently being constructed especially to increase softwood pulp production in Finland. However, an earlier study[15] indicates that even though a strong growth in wood-consumption is expected, there will be moderate impacts on the economy. With the current trend, the productivity of the wood sector is expected to decline. This calls for development and industrial renewal towards new high-value-added bioproducts, which can change the development.

In Finland's agricultural sector, the current cost competitiveness in primary production is poor and the profitability of the sector is expected to weaken even further over the next few years[16]. Likewise in the forest industries, the existing focus of agriculture and food industries on unprocessed raw materials and semi-finished products as the core of exports should be transitioned towards high-value-added goods, thus increasing cost competitiveness. In addition, consumers' increasing environmental concerns and changing eating habits may lead to decreasing domestic demand for meat products and increasing demand for new sustainably produced plant-based food and totally novel protein sources, such as insects.

The share of bioenergy from wood fuels in Finland's primary energy mix was 26% in 2016[2], which is among the highest in the OECD countries. The largest share of bioenergy is produced in forest industries from industrial side streams. However, bioenergy is also produced by municipalities to produce power and district heat. During recent years, an increasing amount of liquid biofuels for road transport have been produced from bio-wastes and from forest-based residuals and industrial side streams in Finland largely due to 2020 climate and energy policies set by the European Commission[17]. In 2015, the share of biofuels was about 15% from total fuel use in transport, which has been a record amount so far[18]. In November 2016, the new Energy and Climate Strategy for Finland to 2030 was launched[19], which includes ambitious targets for renewables both in total energy consumption and in the transport sector. Fulfilling the national energy and climate targets would require an increasing use of biomass, especially wood-based raw materials, for the energy sector by 2030, which is also a prerequisite to reach the new binding 2030 climate and energy targets set by the EU.

The Finnish Bioeconomy Strategy was published in 2014[20] and Prime Minister Sipilä's Government Programme[21] aims at implementing the strategy by including targets and measures to make Finland a forerunner in bioeconomy, circular economy and CleanTech by 2025.

In this report, we have focused on three specific targets of the Government Programme:

- to sustainably increase the percentage of renewable energy, particularly through increasing the supply of bioenergy and other emissions-free energy sources;
- to diversify and increase the use of wood and to raise its value-added material use;
- to improve the profitability of agriculture by improving the profitability and competitiveness of Finnish food production.

It is justified to expect that Finland's bioeconomy sector will inevitably increase by investing in processing of forest and food raw materials into high-value products. However, due to limited natural biomass resources and thus also possible trade-offs of policies and aims to increase Finnish welfare, mitigate greenhouse gas emissions and to protect Finland's nature, it is important to study risks and opportunities of alternative pathways and related decisions. Unprejudiced implementation of innovative and sustainable

production technologies for both bioeconomy and CleanTech, as well as changes in our consumption patterns, values, and other behaviours, would strengthen and accelerate the transition towards a sustainable low-carbon economy.

Feeding bioeconomy

Bioeconomy concept comprises several, different interconnected and overlapping topics such as forestry and wood products, agriculture, fisheries, food, chemical and energy industries, as well as ecosystem services of nature, such as recreation and wellbeing. Digitalization and related services are fundamental parts of the future Finnish bioeconomy, with a growing role domestically but also in exports.

The Finnish forest-based bioeconomy is tightly connected to industrial wood, currently to produce mainly sawn timber, fibre products, power and heat. The approach is to use all fractions of wood in products at as high a value as possible to maximize the material use of wood, taking advantage of low-value residues and side streams as energy. Whereas forest-based bioeconomy can be comprehended through large material flows and the overall picture of wood use, agriculture-based bioeconomy comprises several smaller streams, production steps and units. Faster rotation cycles are also characteristic of agriculture-based bioeconomy. Despite their apparent interconnections, not least through land use considerations, they are treated separately in the following chapters because of their differences in nature and especially in their utilization.

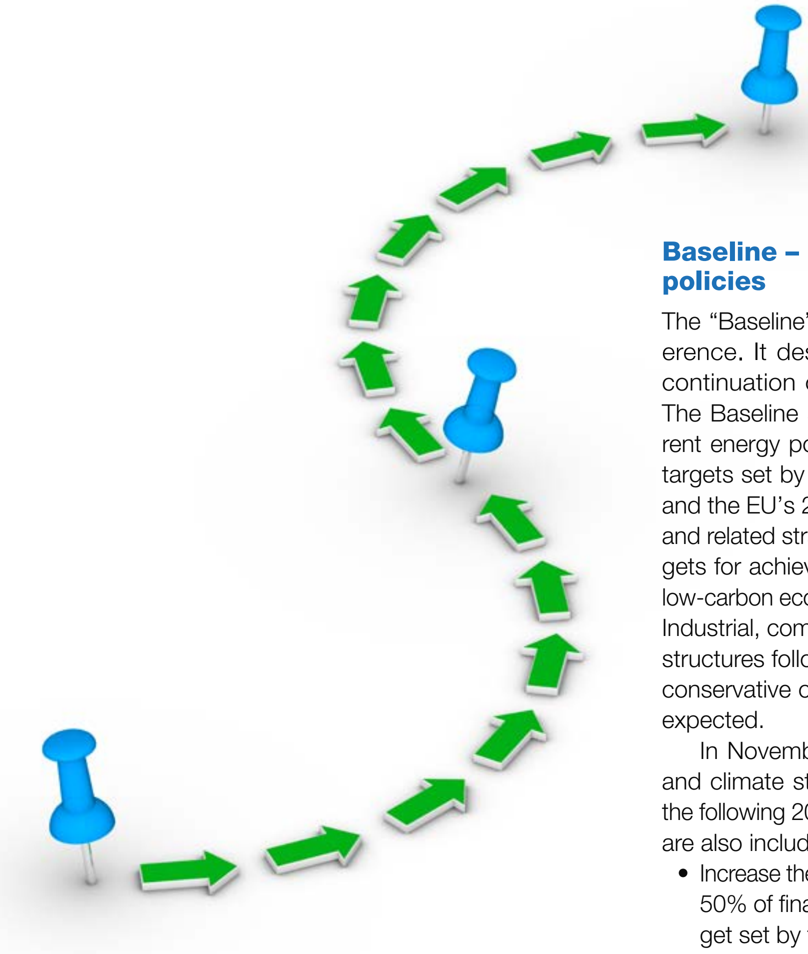
Biomass is a limited resource despite its renewable nature. On a global scale, it is a huge resource, but environmental, social and economic aspects limit its sustainable use. It is therefore crucial to use this resource wisely and in a sustainable way. It will play a an essential role as a source for products, as an integrator in low-carbon energy systems and providing tasty and nutritious food also in the future; it also has several competing uses. Therefore change is driving toward more efficient, value-added uses of this limited resource, which is discussed in the next chapter.

4. Transition scenarios to low-carbon society

Wood-based bioenergy and biofuel production may compete with traditional forest product industries and also with chemical industries using the same type of feed-stocks, like forest residues or industrial side products. Bioenergy may also compete with the food sector, either directly, if food commodities are used for energy or biofuel production, or indirectly, if biomass is produced on arable land that would otherwise be used for food production. Therefore it is important that climate and energy policies consider cross-sectoral impacts on food security and industrial competitiveness. Global sustainable bioenergy potential has been estimated to be between 200–500 EJ/year in 2050[22], while its current use is around 10 EJ comprising about 10% of global primary energy demand. Most of this potential is, however, attributable to agricultural biomass (energy crops, agricultural residues), while the sustainable potential of using forest biomass for energy is already being close to fully utilized. It is therefore understandable that there is substantial uncertainty regarding the long-term global biomass potential of bioenergy, which is largely dependent on global supply and demand for food and also demands for industrial bio-products. The growing global population and improving economic welfare, in addition to changing diets with increased meat demand especially in Asia, increase the demands for food and feed and, thus, decrease global bioenergy potential.

Bioenergy is often considered carbon neutral, as the carbon dioxide released in combustion is assumed to be compensated by the CO_2 absorbed during the growth of trees or other plants. However, because of the long time scales in the regeneration cycle of forest biomass, the sustainability of using wood for energy has been questioned, even when there is a large surplus of growth in forest stocks, like in Finland[23,24]. If forest carbon is released for the purpose of bioenergy production, there is a long-term deficit in the carbon balance compared to the case where the carbon stock is left unutilized in the forest. Therefore, for maximizing resource efficiency in our scenarios for 2050, the primary use of wood biomass is for materials that would decrease the use of fossil fuels, and the energy potential is only a secondary use to be utilized at the end of a cascaded product life-cycle. The use of renewable energy sources thus becomes more diversified by an increased share of solar, wind and other renewables, optimizing the overall efficiency by increased use of biomass resources for balancing of variable renewable energy production.

For illustrating the implications of the bioeconomy in Finland, we have constructed three alternative scenarios leading up to 2050, which will show development paths with different visions and assumptions on clean technology development as well as industrial and societal changes. One scenario represents the Baseline scenario,



including thus Finland's and the EU's energy and climate targets up to 2030. The other two scenarios are so-called "low-carbon scenarios", where global climate change is mitigated below 2 degrees C. The low-carbon scenarios are referred to as Carbon Neutral Scenario (CNS) and BioEco, of which the CNS scenario may use the biomass resources extensively for energy, while in the BioEco scenario biomass is primarily used for high-value products and energy use is constrained by assumed strict sustainability criteria mostly to secondary residues. The three scenarios are briefly described below and in Figure 1, and a more detailed description of the main assumptions behind each scenario is illustrated in Appendix 1. However, in the BioEco scenario greenhouse gas mitigation could be even higher than presented due to more efficient and sustainable use of materials and thus global GHG emission reduction due to land use and its change. Land use, land use change and forestry (LULUCF) sector modelling is not explicitly included in our analysis, which should be kept in mind while discussing the opportunities and challenges of bioeconomy.

Baseline – Current and EU-2030 policies

The "Baseline" scenario is produced as a reference. It describes the future assuming a continuation of current trends and policies. The Baseline scenario thus includes the current energy policy measures in use, the 2020 targets set by the EU, as well as the Finland's and the EU's 2030 energy and climate policies and related strategies. However, no stricter targets for achieving climate change targets or a low-carbon economy are included beyond 2030. Industrial, community, and the whole economy structures follow the present trends and rather conservative clean technology development is expected.

In November 2016, Finland's new energy and climate strategy was launched, including the following 2030 policies and measures, which are also included in the Baseline assumptions:

- Increase the share of renewable energy above 50% of final energy consumption (2020 target set by the EU for Finland is 38%, which has already been reached);
- Reduce the use of mineral oil by 50% (compared with the 2005 level);
- Increase the share of domestic energy sources above 55%;
- Phase out coal in energy production;
- For advanced biofuels, 30% blending obligation in road transport and 10% in oil heating of buildings;
- In transport, the number of electric vehicles is 250,000 and gas vehicles 50,000.

CNS – Carbon Neutral Scenario

The "CNS" scenario sets the ambitious target of achieving carbon neutrality by 2050, meaning that Finland will have a more ambitious target than the overall EU level, e.g. 80% GHG reduction by 2050 compared with the 1990 emission level. The definition and formulation of the CNS is based on the earlier scenario study[25] done in collaboration with the International Energy Agency (IEA), Nordic Energy Research and Nordic research institutes, including VTT. In order to achieve these climate targets, technological development and implementation is assumed to be remarkably fast. Specifically, the energy

Baseline

Current and decided energy and climate policy measures, including EU's 2030 energy and climate policy framework

CNS

Carbon neutrality by 2050
Strong R&D on cleantech, smart and flexible systems and smart cities

Energy
- Smart and flexible energy systems with high self-dependency of fuels and energy
- CCS widely available as a technical solution for energy sector and industry
- Favourable investment conditions for cleantech, including biofuel and bioenergy plants

Forestry and forest industries
- Production of printing papers reached their all-time high production and started to decline after 2006
- Novel products have not successfully penetrated the market

Agriculture and food industries
- Meat and dairy export and production remains on the same level
- Producers favour production of oats over wheat

BioEco

Carbon neutrality by 2050
Strong R&D on new value-added bio-products and circular economy

Energy
- Fossil CCS has not been able to develop as a widely available option
- Radical decrease in costs of solar PV, wind power, and energy storages
- Strict sustainability criteria for bioenergy
- Self-dependency in energy and fuel supply is not as critical measure as in the CNS

Forestry and forest industries
- New product development and demand have replaced decline of paper demand in market
- New ecosystems emerge enabling emerging smaller market-driven business and integration of different scales of production

Agriculture and food industries
- Plant-based diet and novel food products becoming the mainstream
- Meat production is replaced by novel protein crops and production without fields
- Nutrient cycles are closed partly by replacing imported feed supplement protein with domestic protein feed

Figure 1. Characteristics and assumptions in the two different scenarios: Carbon Neutral and BioEco.

efficiencies and costs of low-emission energy production technologies are assumed to develop favourably and global markets of clean energy technologies expand rapidly due to the global climate agreement with the 2 degree C mitigation target and thus increased market prices of emission allowances of greenhouse gases[26]. New production processes are commercialized in many industrial branches, providing a backbone of welfare. The regional and urban form is based on centres with high population densities that provide a promising environment for industrial innovations in ICT and related industries. These regional developments also enable energy-efficient solutions in transportation, such as wide utilization of public transportation, as well as a more dense urban structure, and full integration of smart city concepts and related services.

BioEco – Low-Carbon Bioeconomy scenario

The "BioEco" scenario has as equally ambitious targets for a low-carbon society as the CNS scenario. Technological development is likewise assumed to be fast, but the focus of technological development is somewhat different. Carbon capture and storage technologies for energy production from fossil fuels are not assumed to become commercially viable in the BioEco scenario due to barriers in social acceptance, environmental uncertainties or other reasons. Also in industrial processes, application of CCS is constrained leading to industrial transformation, like in steel industries. Bioenergy utilization in this scenario is assumed to be constrained by stricter sustainability criteria, which slows down technology development of advanced biofuel conversion technologies. Consequently, the electrification of the transport sector is accelerated in the BioEco scenario. As a counterbalance, the use of other renewables develop more rapidly than in the CNS, supported by energy storage, power-to-fuel and fuel cell technologies. Regional and urban development are assumed to be similar to the CNS scenario.

4.1 METHODS AND DATA USED IN THE SCENARIO ANALYSIS

The energy system model TIMES-VTT is a global multi-region model originally developed from the global ETSAP-TIAM model[27], which has been developed under the IEA ETSAP (Energy Technology System Analysis Programme). The model is based on the ETSAP TIMES modelling framework, and is characterized as a technology-rich, bottom-up type partial equilibrium model[28]. The TIMES-VTT model consists of 17 regions, which include four Nordic countries (Denmark, Finland, Norway, Sweden) which are individually modelled, while most of the other regions are aggregates of several countries[29]. As in bottom-up models in general, by far the largest amount of input data is required for the various existing and new technologies available in the energy system. The technology data have been collected from numerous sources, and have been further classified into base estimates and optimistic ones. In this study, base estimates have been used for the Baseline and rather optimistic values for the CNS and BioEco scenarios (see Appendix 1). A considerable amount of technology data is also based on expert judgements by numerous VTT technology experts.

For gaining further insights into the macroeconomic impacts of the low-carbon pathways, the FINAGE model was soft-linked with the TIMES-VTT model. The FINAGE model is a dynamic, applied general equilibrium (AGE) model of the Finnish economy, based on the MONASH-model[30] and VATTAGE models[31].

Both TIMES-VTT and FINAGE (or their earlier versions) have been used for background studies of Finland's energy and climate strategies, including the 2016 strategy and the medium-term climate plan for Finland. In addition, these models were used to assess alternative scenarios for the Low-Carbon Roadmap 2050 for Finland[32]. Models and databases are constantly updated and developed further with international collaboration[33].

5. Pathway to a new product structure of future bioeconomy?

5.1 FOREST INDUSTRY CHANGING TO ECOSYSTEM TYPE, NEW VALUE-ADDED PRODUCTS REPLACING DIMINISHING PAPER

”Where are we going?” - Forest industry drivers

Structural changes began in the forest industry both globally and in Finland in the early 2000s, when the production of printing papers reached an all-time high production and started to decline after 2006. The main reason can be found in the rapid development of digital data communication[34]. The recent evolution of business has been characterized by investments in other uses, such as bioenergy and board production, as well as development of soft paper and hygienic product offerings. According to the analysis by McKinsey[35], graphic papers, particularly newsprint and coated papers, but also uncoated papers, will continue to decline while consumer and industrial packaging, as well as tissue, will grow roughly in line with or somewhat below GDP. They also see that hardwood fibre is likely to face near-term challenges despite demand growth, but for the softwood fibre the situation looks much promising.

The accelerating impact of investments in cardboard in Finland can be estimated to be reached by years 2023–25. As of spring 2017 there was a total of five major bio-refineries or, in the other words, advanced contemporary pulp mill projects in Finland only, and they are targeting to be on-stream by the early 2020s[36]. In the next five years, investments in bio-refineries are expected to total some 5 billion euros.

The Pellervo Economic Research Institute has studied the economic impact of pulp and paper, wood-based bio-refineries and energy sectors in Finland by year 2035[37]. According to the research, the use of wood will increase markedly, ca. 14% more compared to the 2015 level, but simultaneously productivity of the forest industry will decrease due to increased production of low-value-added products, like pulp. This may compromise economic growth compared to the targets set by the Finnish Bioeconomy Strategy, especially if the forest industry in Finland concentrates on pulp production instead of paper.

There have been increasing concerns about the sustainable wood supply, including the impacts of increased use of wood on our natural ecosystems and climate. The Government has set a target to increase the consumption of domestic stemwood from the current level of about 65 Mm^3/a up to 80 Mm^3/a. In addition, the role of wood-based bioenergy and advanced biofuels is projected to be significant in order to reach the 2030–2050 energy and climate targets (see Chapter 6). Potentially, measures of forest management, like applying fertilizers, could compensate the impacts of the collection of energy fraction (for example, harvesting residues and stumps) on soil. However, these measures also have their limitations and risks[38]. On the other hand, the increasing role of forest-based bioenergy in achieving the long-term climate policy targets is uncertain due to policies and measures related to land use and its change, and forestry (e.g. LULUCF), which could also steer the use of wood raw materials and industrial side products towards products with longer lifetimes or higher value than energy only. Hence, we can expect that a sustainable wood supply would be adequate for increased industrial use due to forest management and increased efficiency of material uses.

To conclude, the investments in the existing production structure will reach their maximal impact by the end of the 2020's. There is an evident need to renew Finland's industrial structure to produce higher value-added products from wood. One of the main emerging product groups, the already-mentioned hygienic and textile materials, are experiencing growing demands due to the increasing global population and improved welfare. It has been estimated that cellulosic fibres could make 30–40% of the textile fibre demand in the beginning of the 2030's, which would result globally in some 10 million tons cellulose gap[39].

The replacement of plastics can take place predominantly through fibre materials, for example novel materials like mouldable web and novel packaging material innovations. The replaceable polyester packaging global market represents over 15 million tons and that for polystyrene over 5 million tons. The polyolefin (e.g. polyethylene and polypropylene) replacement is less obvious, because of affordable shale-gas resources and thus utilization of low-cost natural gas as a raw material. However, certain applications, like plastic shopping bags, might be limited by legislation. As an example, the EU has already set new regulations to limit the use of non-renewable plastic bags[40]. However, the breakthrough of thermoplastic cellulose materials is not yet foreseen due to high production costs of fibre-based materials.

The research and development of completely new products will continue actively and they will be introduced in increasing numbers towards the end of the 2020's. However, the actual breakthroughs can be expected only in the 2030s due to needed revolutions in material use. As an example, typical for the novel materials are information content and value added comparable with plastic and composite materials. Already foreseen novel fibre products now range from use of nanocellulose as a barrier material or reinforcements, e.g. in plastics,

Fibre web

Increased demand for hygiene and wiping products is related to the change in consumer behaviour and standard of living increases in some parts of the world. Nonwoven fabrics are the backbone of those industries, but oil-based fibres currently used in production are an environmental challenge to be utilized especially in disposable products that are challenging to recycle. Nonwoven fabric production can, however, be integrated into pulp production, just like paper production earlier, to obtain renewable bio-based products.

By combining advanced, long fibre web production technology with textile fibres, it is possible to take an innovative approach to a sustainable consumable market. The most potential value-added products from refining nonwoven fabrics are in packaging, hygiene, or cosmetic products. One example of this kind of packaging product is nonwoven bags, that can replace plastic bags.

Mouldable board creates a totally new type of material for packaging alongside corrugated cardboard, folding boxboard and liquid packaging board. The current societal trend toward smaller families directs consumer behaviour towards more processed convenience food. Individualized packaging for food products and ready meals often requires plastic packaging. Mouldable board offers a recyclable and renewable material to replace plastic in these growing markets. Replacing the oil-based plastic barrier layer in paper cups will be essential in this segment. Also, new types of packages, such as self-standing bags for soups, prepared food and dried products change packaging from conventional tin cans and glass jars toward a more sustainable and efficient direction.

to a multitude of uses for thermoplastic cellulose. Expanding demand for alternative textile materials, e.g. based on dissolving pulp and nonwovens especially in hygiene products, are seen as fast growing market segments. New solutions for liquid packaging and self-standing packages require new cardboard solutions as well as demanding barrier properties for new products. Hemicellulose-based products such as bioplastics, barrier materials and dissolving films complete the product portfolio of the future with lignin-based products. Most potential product categories based on lignin are, e.g. materials for automotives of the future and wood glues and adhesives. Breakthroughs in the manufacturing of micro and nano-cellulose have been made, but the applications and converting of these materials is still under development[41]. Their novel application fields are expected to be found, e.g. in the vehicle and electronic industries. The importance of cellulose films will be pronounced. Recently, increasing attention has focused on personalization and 3D printing. Further, novel products and digitalization will change the traditional structures of the market and the existing distribution channels.

Bioenergy will find added value use while the emerging productions will be integrated with the bio-refineries. In addition, in the long term the importance of carbon dioxide capture use and storage can play a significant role either as an enabling technology for indirect electrification (CCU) or mitigating historical greenhouse gas emission or emissions across sectors (CCS)[42]. Integration into process and flue gases of pulp and paper industries as well bio-refineries and energy plants may considerably increase the competitiveness of these industries in relation to a future climate regime. The forest industry is a marked source for biogenic carbon dioxide, which could be applied in process aid or intermediate for chemicals[43]. However, this Bio-CCS and Bio-CCU can only indicatively be estimated because no policies exist yet that give high enough incentives for so-called negative CO_2 emissions, i.e. removing CO_2 from the atmosphere.

5.1.1 Wood flows and products in three alternative scenarios

The primary objective of the scenario assessments was to investigate the impacts of substituting fossil-based resources by new bio-based resources to both mitigate GHG emissions and to enhance sustainable use of renewable materials and energy. Another important objective was to visualize how the forest sector could create new business and increase wellbeing through new products and services. The scenarios also entail the objective of a circular economy, which aims to maximize the full life-cycle and value of

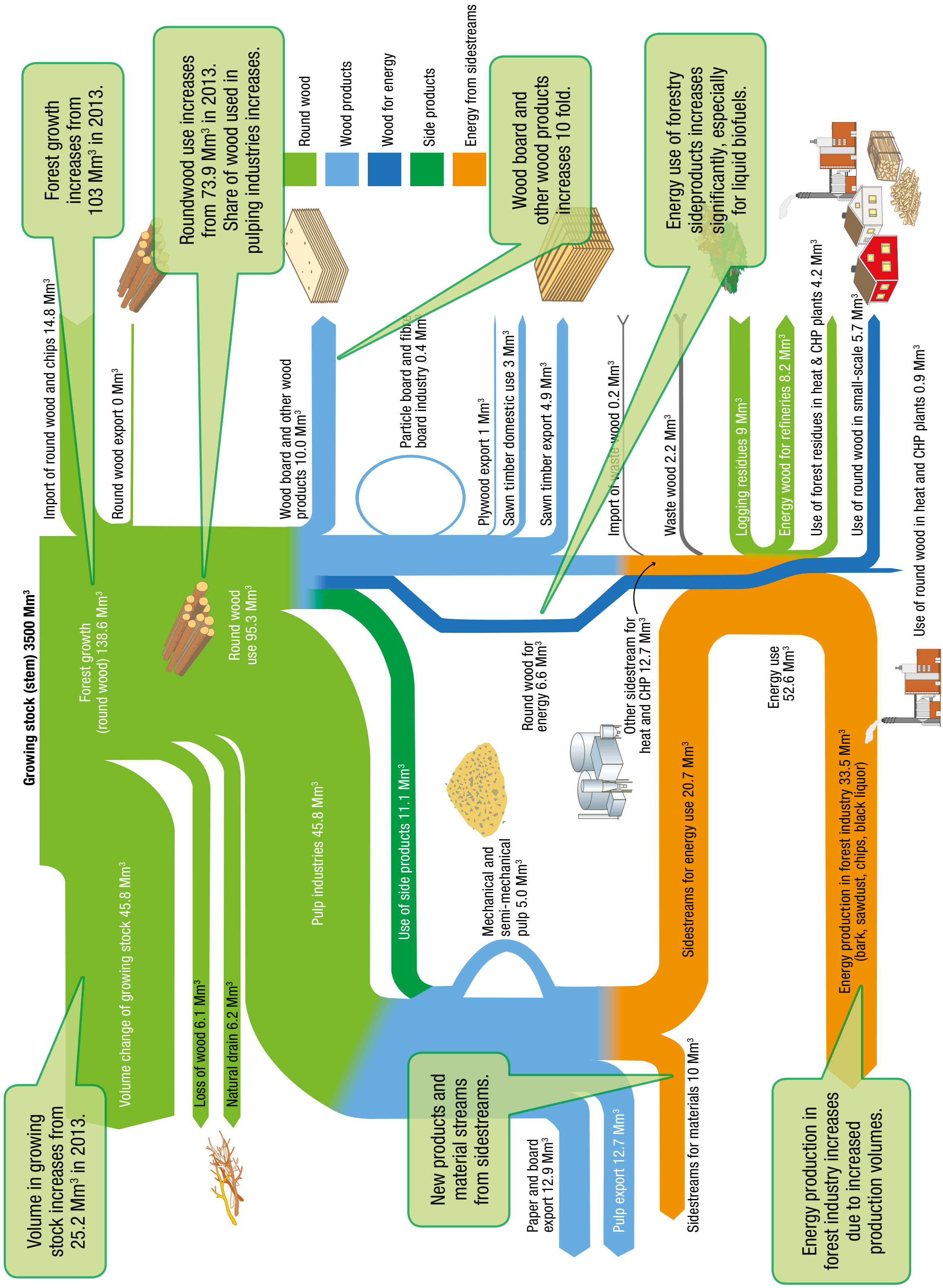


Figure 2. Presentation of wood flows in 2050 in the BioEco scenario and major changes in comparison with the current situation.

materials and products in the economy by utilizing them in a cascaded manner.

In our three scenarios, domestic wood resources are utilized differently: In the Baseline and CNS scenarios industrial structure follows the path, which largely corresponds to the existing product mix and expectations of increased pulp production while graphic paper production declines. Up to 2030, the Baseline and CNS scenarios for forest industries follow the path assessed by Pöyry[44]. These assessments were also used in the latest Energy and Climate Strategy of Finland. In the BioEco scenario, new forest-based products are expected to enter global markets after 2030 with increased material efficiency and added value. In Figure 2, schematics of wood flow assumptions in 2050 into different products are shown. A more-detailed presentation of wood flows in 2013 and 2050 in different scenarios is shown in Appendix 3. Figure 2 shows that the greatest differences compared to the today's situation lie in a greater share of wood use in the pulping industry and expansion of wood industries as a whole, which is seen in both the CNS and BioEco scenarios. In the BioEco scenario, we have also expected that new products and materials from lignin and cellulose are produced and the export of wood products increase remarkably, while the export of sawn timber declines. In addition, we have assumed that in the BioEco scenario the sustainability criteria of using wood raw materials for bioenergy or biofuels are stricter than in the Baseline and CNS scenarios.

Value added of new wood-based products in the BioEco scenario is illustrated in Figure 3. It can be seen that the value added of traditional pulp and paper products are declining, but if the new products enter the market, value added could even double from the current level. As an example, production and export of furniture, wooden houses, and other products are expected to be produced and exported instead of sawn timber. Lignin is one of the largest by-products of the forest industry in addition to tall oil and turpentine. Lignin could be used to produce substances found in glues and chemicals, possibly also in technical carbons, e.g. absorbing carbons or metallurgic carbons. Wood glue markets only represent a few million tons. Lignin availability will increase as a result of revamping pulp mills, but due to the energy

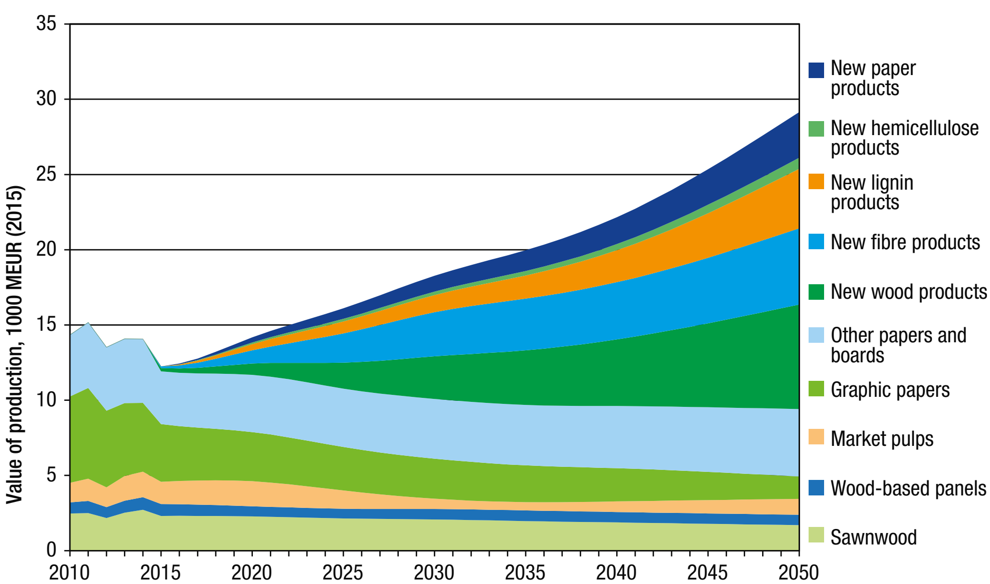


Figure 3. Value of production of wood-based products in the BioEco scenario.

self-sufficiency requirement of pulp mills, polymeric lignin recovery has to be limited to 20% of total production. The importance of other side streams, like tall oil, may have a local impact.

The total supply of domestic stemwood increases to about 82 million m^3 in the CNS scenario, and to about 80 million m^3 in the BioEco scenario by 2050. This amount includes industrial roundwood, firewood and the smallwood fraction of primary forest residues (see Figure 4). Due to the assumptions on stricter sustainability criteria in the long term, the amount of smallwood use is reduced to less than 1 million m^3 in the BioEco scenario, while it is close to 8 million m^3 in the CNS scenario. Nonetheless, in both scenarios the total use of domestic roundwood remains well below the assumed maximum sustainable volume of annual stemwood removals, which is estimated to be about 86 million m^3 in the year 2030[45], and with the past trends continuing, probably over 90 million m^3 by 2050.

Due to the considerably larger need for industrial pulpwood for bio-materials in the BioEco scenario, the imports of wood would increase to 14.8 million m^3 by 2050, while the imports were about 10 million m^3 in 2013. However, if we compensate for the favourable difference in the total stemwood use, the increased wood import would be only about 3 million m^3. In any case, as long as the imported wood can be assumed to come from sustainably managed forests, and used for high-value bioeconomy products, the risk of unsustainable wood utilization can be considered to be lower in the BioEco than in the CNS scenario. Due to the assumptions on stricter sustainability criteria, this is highlighted by the use of wood for energy, which is about 100 PJ smaller in the BioEco scenario, and is only 11% higher than in 2013 (see Figure 5).

The balance in the supply and consumption of liquid biofuels also becomes somewhat less favourable in the BioEco scenario (see Figure 6), but as the sustainability criteria for bioenergy were assumed to be strict, the imported biofuels should also comply with these criteria. Finland would thus focus on using biomass for high-valued products, while importing lower-valued bioenergy products as long as their sustainability is reliable.

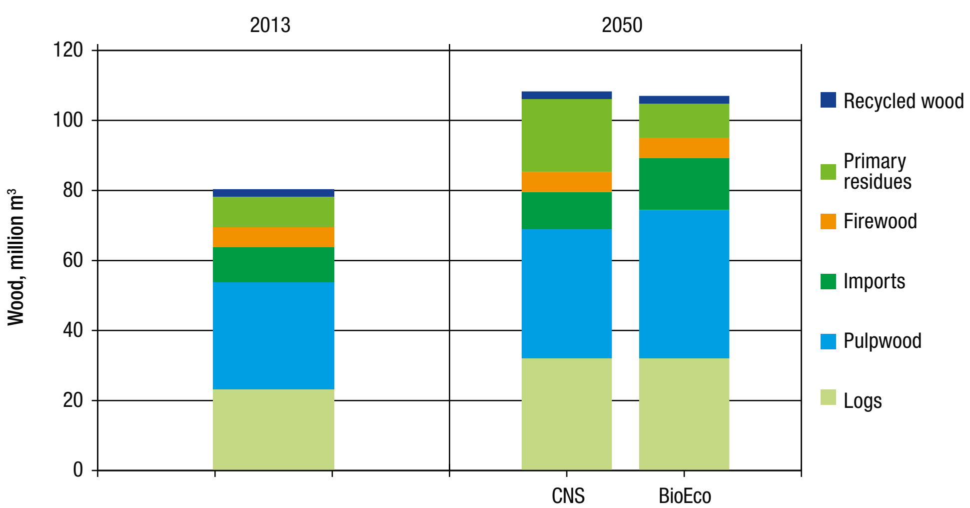


Figure 4. Supply of wood in 2013 and 2050 according to the CNS and BioEco scenarios.

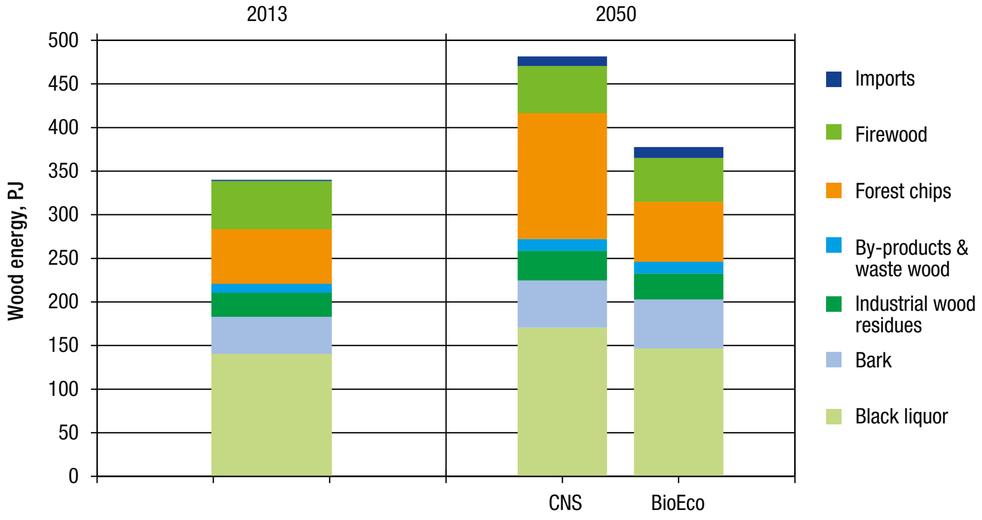


Figure 5. Use of wood for energy in 2013 and 2050 according to the CNS and BioEco scenarios.

Novel fibre products

Nanocellulose is a novel bio-based and environmentally friendly nano material that is comprised of filament and rod-shaped celluloses, that are very small in size, typically smaller than 100 nm (10^{-9} m). The production is possible based on existing cellulose production and enables value added use for widely available intermediate products. Nanocellulose is an extremely versatile material and additive with numerous uses, such as increasing barrier properties of packages, reinforcement of board web or in electronics and supercapacitors.

Energy-efficient vehicles, like electric cars of the future will need vast amounts of affordable carbon fibre to strengthen composite materials that are used in their construction to save weight and improve properties. New fibre technologies enable production of high lignin content continuous fibre that can be carbonized into high-quality carbon fibre.

Textile use is increasing as the global population increases and standard of living improves. At the same time availability of cotton is even decreasing and synthetic, oil-based textiles are causing increasing environmental concerns. Wood-based textile fibres produced from dissolving pulp are an environmentally sound solution for the textile industry. Several pulp mills, which are too small to economically produce market pulp, are planned to be converted to produce dissolving pulp. Also, completely new plants are being planned to satisfy the growing need. New, wood-based textile fibre production methods ensure unparalleled quality and environmental improvements for textiles. Cellulose carbamate fibre, replacing viscose and Lyocell produced with ionic liquids, are a few potential alternatives.

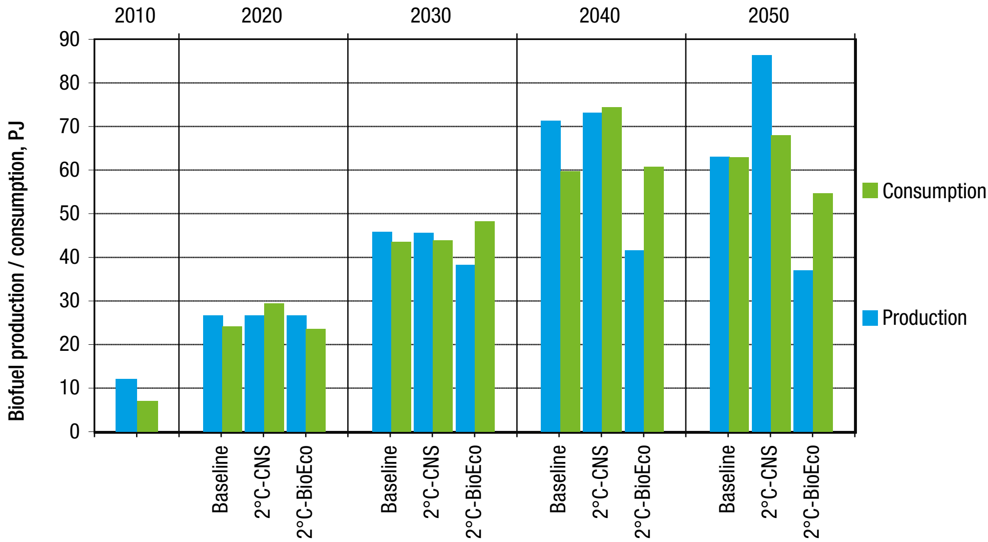


Figure 6. Biofuel energy balance in the Baseline, CNS and BioEco scenarios [5,6,7].

Biochemicals

Dissolving plastics and polymers are utilized in various applications. The increased use has awaken a growing concern on microplastics in the environment. Dissolving films are, for example, utilized in packaging of dishwasher tablets preventing skin contact, as detergents can irritate skin. When dissolving, the polymer ends up in to the water system. Biodegradable, e.g. hemicellulose-based films, can however completely avoid this problem.

Functional materials, such as barrier materials preventing passage of, e.g. oxygen or grease, have been a key success factor in development of coated fibre web. Advanced polymers, such as polyglucolic acid are used to obtain required properties. This particular polymer is biodegradable, and at the same time one of the best oxygen barrier polymers. This can also be utilized as a precursor of bioplastics, and production could be integrated into existing processes of forestry.

Growth of bioplastics is based on the need to reduce fossil oil dependence and increase sustainability. Thermomouldable cellulose can replace plastic and be a more environmentally friendly alternative to even existing bioplastics in, for example packages, coatings and structural materials. Thermomouldability enables use of existing techniques and machinery in the plastics industry. Also, individualized 3D printing-based solutions are possible.

Value from lignin side-streams

Lignin is the most important by-product from the lignocellulosic biorefineries, and a valuable renewable resource for the chemical industry. The pulping industry is the major source of lignin, but substantial amounts of lignin-rich side-streams are expected to originate from bioethanol production in the future. Based on the annual pulp production capacity of 7.5 million tons[46], approximately 3–4 million tons of lignin is extracted from wood as a by-product of the Finnish pulping industry. Roughly 20–25% of black liquor lignin could be recovered without compromising a pulp mill's energy demand. Hence, approximately 0.6–1 million tons of kraft lignin could be produced annually in Finland for higher-value material purposes, offering new business opportunities for the Finnish pulp and paper industry. Due to a low ethanol price, the valorization of lignin side-streams is even more important for the cost-competitive bioethanol production via sugars. Among sustainability, the stable and cost-competitive price compared to the current oil-based raw materials are the main drivers for lignin use in the chemical industry, which along with the valorization of lignin, has the potential to significantly improve the cost-competitiveness of lignocellulosic biorefineries.

Lignin oxidation technology for versatile dispersants

The LigniOx technology is a simple and cost-competitive lignin functionalization method based on alkali-O_2 oxidation for production of versatile lignin-based surface-active agents. The anionic LigniOx lignins can find application possibilities in several end-uses with high market volumes, e.g. as high-performance concrete plasticizers and versatile dispersants. The global demand for plasticizer admixtures alone is up to 15 million tons annually. It has been shown that the technical performance of LigniOx lignin in concrete plasticizers is better than with commercial lignosulphonate plasticizers, and can compete even with some synthetic plasticizers. The results also show potential for replacement of synthetic dispersants, e.g. in paints and coatings. By adjustment of oxidation conditions, the lignin properties can be fine-tuned to a wide range of end-products. The method is also well applicable to lignins originating from different raw materials and processes. The oxidation is performed using low-cost bulk chemicals (NaOH, O_2) and can be well integrated into lignocellulosic biorefineries. Caustic and oxygen are commonly used at pulp mills, and are thus compatible with the current chemical circulation. Operation in stand-alone units by the chemical industry is also possible.

Highly reactive lignin for phenolic resins

Lignin use in phenolic resins, e.g. for wood adhesives, is one of the most promising potential end-uses of lignin. Wood construction is increasing, leading to increased demand for efficient wet-strength adhesives for increased use engineered wood structures. For the resin producers, lignin offers a cost-competitive, bio-based, non-toxic raw material for replacement of phenol. However, with the current commercial lignins, the phenol replacement levels are rather moderate (20–40%) due to the lower reactivity of lignin compared to phenol. To reach higher utilization degrees (50–100%) enabling more substantial cost reduction in resin manufacturing or fully bio-based products, lignin reactivity needs to be improved. VTT has developed and patented a simultaneous lignin separation and activation process that produces highly reactive catechol-rich lignin, CatLignin, enabling high phenol replacement levels without any additional activation treatment. As a result of this, the total resin manufacturing cost can be significantly lower than with the conventional phenol formulations or using any currently available commercial lignins. For pulp mills, the technology offers an entry with a lignin product with tailor-made properties to a growing high-value market and will potentially open the door for multiple other high-value lignin applications.

5.2 AGRICULTURAL SECTOR

”Where are we going?” - Drivers in agriculture

The overreaching goals of bioeconomy are food security and sustainable resource management. Even though in Finland the forest-based biomass is the major biomass resource, it should be recognized that globally food and feed together account for the majority of global biomass demand. These products are generated by agriculture (including livestock), horticulture, fisheries and aquaculture.

Global population growth, increasing consumption of water, energy and food, increased greenhouse gas emissions and also improvement of living standards in large developing economies cause pressure for changes towards better sustainability and resource efficiency in agriculture and food production, as well as in food consumption habits. High population growth in the next few decades will mainly occur in Asia and Africa, with any change in Europe potentially being a slight decrease. However, the pressure for change towards better sustainability is bound to affect also Finland as a part of the global economy.

The major driver of global dietary change and the demand for food and feed is originating from Asia, such as China and India, due to the growth in their economies and populations. Changes in European diets are predicted to be small, and the main demand impacts on Europe will mainly be the consequence of global trade, unless consumers respond to the efforts of governments to tackle diet and health issues[47]. However, European eating habits are gradually changing. Meat is increasingly replaced by other, more sustainably produced protein sources, as multiple plant-based meat and milk analogues are available on the shelves of food shops. In sustainable development, red meat, i.e. beef and pork, are increasingly substituted by protein crops such as pulses and farmed fish, poultry and insects. This shift to ‘other than red meat protein’ will reduce the environmental load caused mainly by cattle due to decreased manure production, GHG emissions (mainly CO_2 and CH_4) and grazing.

Protein mining of cereal side-streams exploring novel technological concepts

From the perspectives of sustainability, food security and human health, there is a global need to increase dietary intake of plant protein. Side-streams from wheat and rice processing offer a large under-exploited raw material potential. Novel hybrid fractionation and extraction technologies, utilizing bioprocessing, supercritical carbon dioxide extraction, thermo-mechanical technologies, wet and dry fractionation, and expanded bed adsorption technology enable generating new plant protein ingredients obtained from cereal processing side streams as well as new products for the consumer food market. Focusing on enzymatic and thermo-mechanical methods to improve techno-functional and sensory properties of protein ingredients will enable reaching desirable taste and texture in food applications. Pasta, biscuit, cake and beverage food models are the main end-product categories, where new protein ingredients will be used as a dietary protein source and act as performance proteins to deliver similar techno-functional and sensory properties to animal proteins.

5.2.1 Changes in agriculture and agricultural products in alternative scenarios

The primary objective of the scenario assessments of the agricultural sector was to investigate the impacts of changing behaviour, e.g. diets, on GHG emissions and the environment. Therefore the descriptions of the below alternative scenarios are more based on "story telling" than in the above case of the forest sector. However, the objective was also to visualize the possible impacts of new value-added food and feed products on the growth of food industries and Finland's economy. The objective of a circular economy is considered, especially through processing of manure, including nutrient recycling.

Carbon-Neutral Scenario – changes in food production and consumption are predictable

In the Carbon Neutral Scenario (CNS) the assumed demands for food and feed, primary production of food raw materials and food production change in a predictable and restricted manner. Agricultural production up to 2030 follows the basic assumptions used in Finland's Energy and Climate Strategy. After 2030, the total amount of meat consumption will be on the same level, however poultry meat and fish will replace use of beef. Side streams of food production and processing are increasingly upgraded for food use. In the CNS scenario, cereals production slightly decreases. The emphasis between cereal species may vary favouring oat production over wheat. The clearest production increase will be seen in protein-containing plants such as rapeseeds and pulses. Silage production slightly decreases in the CNS scenario, due to a decrease in meat and milk production. However, grass silage is thought to be suitable feed also for monogastric animals. Although red meat and milk production will be reduced, an increase is seen in broiler chicken production and fish farming.

In Asia, consumption of pork and chicken will grow especially due to the increase of living standards in these countries. China and India, particularly, are vast economies and they are expected to increase their meat import from Europe and America. This change will offer Finland a growing possibility to export meat and

Smart recycling technology for bakery side streams

The bakery industry is one of the major food industry branches in Finland and Europe producing 18 million kg of bakery side stream/waste (7.5% of total production volume) per year due to production losses. However, the majority of bakery side stream is completely eligible to be reused in the food industry and should not be wasted by removing it from nutrient circulation, especially with increasing challenges in future food security and environmental consequences of waste. Non-recyclable waste can be converted to biogas at bakery locations. Currently, the main utilization of these side streams is as animal feed, biofuel production or landfill. The current sub-optimal situation is an economic burden for bakeries, who lose income every day due to unsold bakery products and have significant extra costs from waste collection, storage and transportation.

feed grain to Asian markets. Meat export will be made possible by a downturn in domestic red meat consumption. Expanding export may cause shortages in domestic grain availability for feed and food use. As a consequence, oat cultivation will thrive and production volumes increase. Production of rye will remain on the present level, but wheat production will decrease to a certain degree. The hiccup in rapeseed production due to the current EU ban on neonicotinoid insecticide use as a seed coating agent will be transitory. Return to the present rapeseed production level within a decade is expected. After that, rapeseed production will increase clearly. The reason is the increasing demand for rapeseed protein, seen already now, as a food ingredient. Protein will become the primary product of rapeseed processing.

Meat production will remain at its present level or even grow slightly because of the refreshed export to Asian markets. On the other hand, domestic red meat consumption will decrease due to consumer awareness of the unsustainability of red meat production and consequent growing demand for plant-based food, ingredients and raw materials. Plant-based diets will become more common but not the main stream. This will lead to increasing cultivation of domestic protein crops, both for food and feed. At the same time, soy, an imported plant protein source, will decline to less than half the current amount. Conversion of grass or ensiled grass by advanced technology to appropriate feed for monogastric animals, pigs and poultry, will become common, but grass cultivation will not increase. Increasing domestic feed protein production enables limitation of soy import, which leads to a desired improvement in domestic feed protein self-sufficiency.

In the CNS scenario, meat and milk production will only slightly decrease compared with the Baseline. The manure load (nitrogen, phosphorous) will somewhat decrease due to processing of the a major part of manure and GHG (methane, CO_2, ammonia) emissions from animal husbandry will remain at the same level, partly due to supplemental feed import. Especially due to the relatively high non-CO_2 GHG emissions from the agricultural sector, which are very difficult to mitigate, increasing pressure is put on other GHG-emitting sectors to cut their GHG emissions. On the other hand, if the nutrient flow from soil to waters and addition of nutrients to this flow, as mineral fertilizers and imported feed cannot be prevented, eutrophication of the water systems will continue. Liquid nitrogen originating from manure can be used increasingly as a forest fertilizer (if logistically feasible). Ammonia, methane and CO_2 emissions to the air from animal husbandry need to be solved. In addition, managing manure phosphorous and nitrogen necessitates advanced technology yet to be developed and commercialized.

Low-carbon bioeconomy scenario – meat production and consumption decreases drastically

Unlike in the CNS, in the BioEco scenario, we have expected radical changes in our diets. Consumption of meat, especially beef and pork, will decrease dramatically in Western countries as well as in Asia due to changing eating habits and unavoidable need to make global food production more efficient and environmentally benign. This development affects Finland by drastically decreasing red meat production and to a certain degree also milk production. Broiler chicken production is predicted to grow. The pivotal reasons are yet early to predict, but the high price of meat due to unavailability will be, by definition, a strong driving force in the BioEco scenario. The pressure to increase price is easily explained by a worldwide collapse of red meat production due to potential regulations limiting production animal husbandry and making it unprofitable because of too severe environmental impacts and its inefficiency to produce food for the growing population.

Accordingly, sustainably produced plant-based meat and milk alternatives and foods in general will take over the global food market and compete successfully with animal-based products. Plant foods will be lucrative compared to meat. They are healthy, attractive and can be produced without fields and with minimal waste, e.g. in urban and vertical farms and bioreactors. Increasing awareness of the environmental impacts of meat production will affect eating habits and food choices of conscious consumers worldwide, not only in Finland, Europe and other western countries. This will inevitably lead to lessened demand for meat. Nevertheless, food of an animal origin will not be abandoned. Besides plant foods meat will be replaced by fish farmed increasingly and sustainably in tanks on land with efficient water usage by circulation. Farmed fish production will double in Finland.

In addition to plant-based foods and farmed fish, consumption of insects as a protein source will increase in Western countries. Liberation from the regulation ban, coming into force in 2018, will boost the production of food insects and insect-based foods in Finland already in the near future.

In Finland, beef production will be abated to near zero, and pork production will be reduced to one half of its current level. Milk and poultry production is expected to be maintained at existing levels, although vegetable-based replacers for milk and eggs will be on the market. Milk cannot be directly substituted by plant alternatives in the balanced nutrition of infants and small children. Finland is the best country in the world regarding the availability of a versatile supply of healthy milk-based products. This will be a barrier against reduced domestic milk production.

Collapse of red meat production will affect food and feed grain production and consequently their export. Cereal crop cultivation in total will be reduced to less than a half of current amounts, the reduction hitting mostly wheat. Instead, oats production will remain or eventually overpower cereal production, because this grain crop has established its position as a desired and increasingly popular food cereal. The use of oats will shift completely from feed to food use. Reduction of food cereal production is compensated by increased cultivation of oil crops and pulses, such as horse bean and pea. Cereals as a source of feed and possibly food will be partly replaced by grass or ensiled grass processed to be suitable feed for monogastric animals and eventually for food. Meat protein will be compensated by doubling the production of farmed fish and fortifying the production of food insects. Reduced red meat production limits discharges to the environment. Nutrients will be recycled in a balanced way and leakage to waters and emissions to air will be controlled. The farmed land area no longer needed for feed production can now potentially produce more novel crops for food and material use both for export and domestic use. Figure 7 and Figure 8 depict the changes of agricultural biomass flows and the value of production of agricultural-based products in the BioEco scenario.

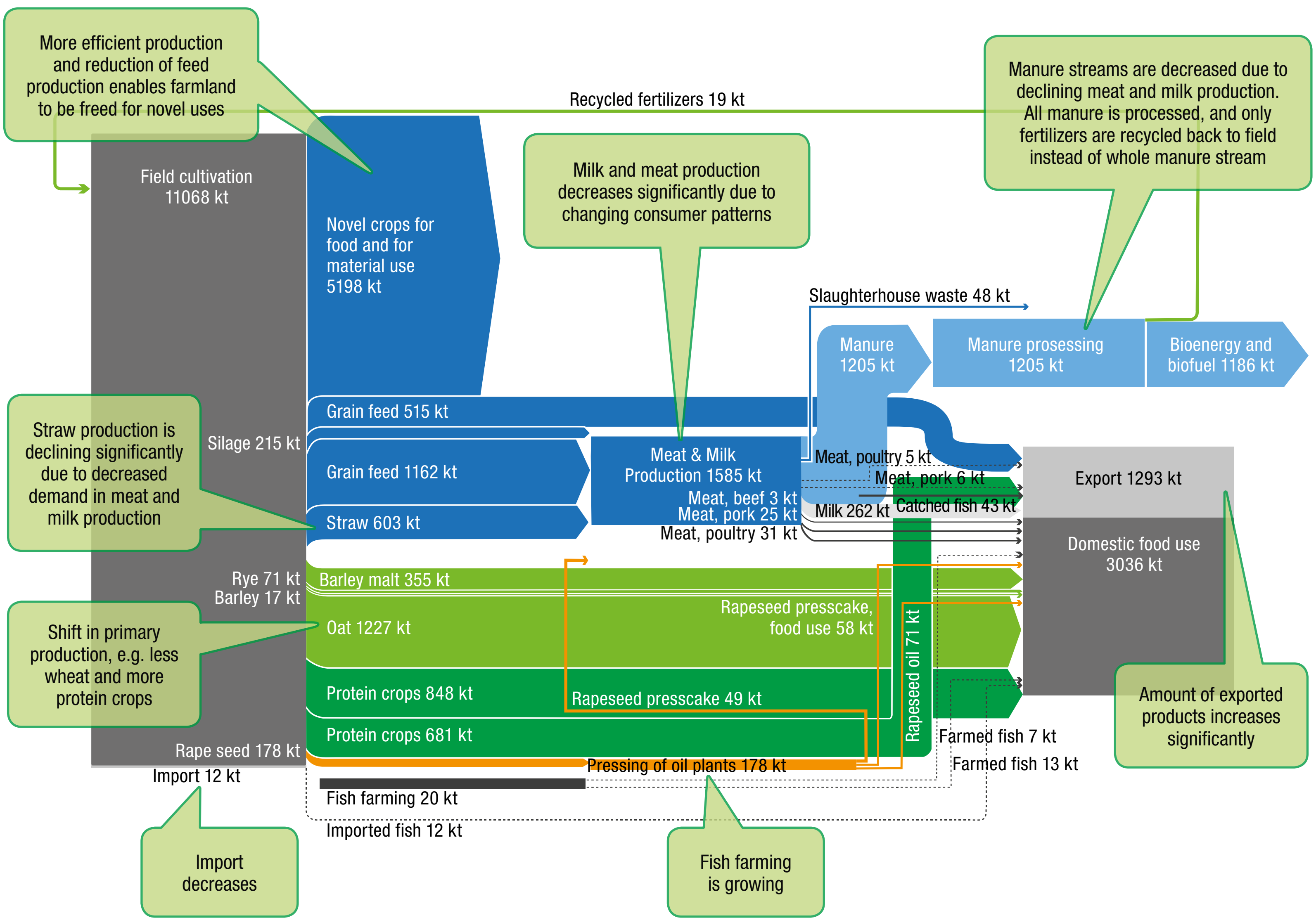


Figure 7. Agricultural biomass flows in 2050 in the BioEco scenario and major changes in comparison with the current situation.

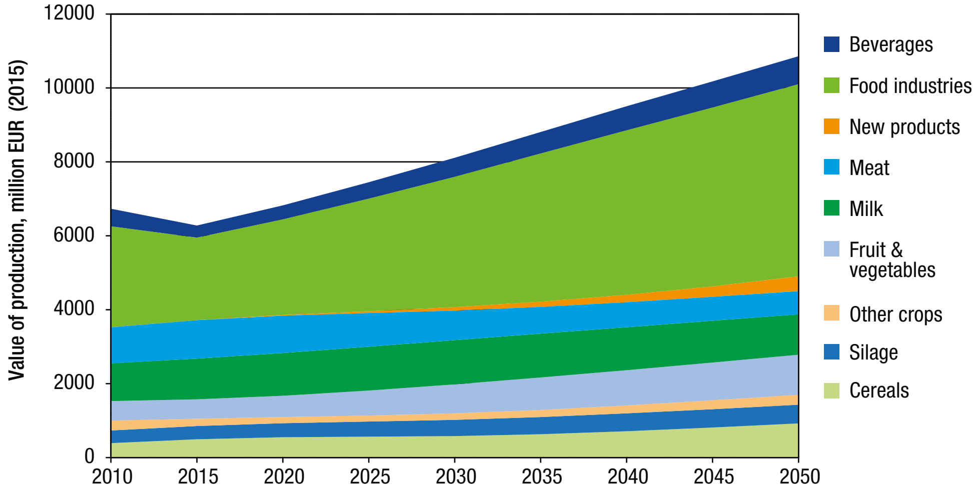


Figure 8. Value of production of agricultural-based products in the BioEco scenario.

Biorefineries turn grass into new feed products

Feed made from grass contains mainly lignocellulosic fibre but also plenty of protein and soluble sugars. A technology under development will convert ensiled grass (silage) to suitable and nutritious feed for monogastric animals, such as pigs and poultry. Profitability of farms will be improved with the help of technology that will be used for producing feed products from silage offering higher added value and at the same time, improve low protein self-sufficiency, which is only about 15% in terms of protein supplementary feeds in Finland. Developing models for both farm-specific and centralized biorefineries that produce new feed products will enable developing production methods that will not require costly investments on farms.

In the future, grass will be converted to various feed products, such as protein-rich and sugar-rich "feed juice" and solid feed fortified by single-cell protein. The cellulose of the forage can be broken down into sugars that can then be used for producing feed protein with the help of a yeast or fungus. The nutritional value and preservability of feed juice products can also be improved via the action of lactic acid bacteria. Through ensiling, grass biomass can be refined all year round. Due to the high protein and low lignin content, grass is much easier to process into fractions of sugar and protein than wood or straw, for example.

According to the Natural Resources Institute Finland, there is potential in Finland, in addition to the current feed use, to produce grass on an area of 470,000 hectares that could be used as energy and other new applications. If the crop totalled 5,000–8,000 kg/hectare/year, this would correspond to a biomass production potential of 2.3–3.8 million tonnes of dry matter. By including grass in the cultivation cycle, the erosion of fields can be reduced, biodiversity can be increased, and the structure of soil and the cycle of nutrients can be improved. This would be particularly beneficial in Southern Finland where cultivation cycles are often one-sided.

Alternative protein sources – from sustainable fish farming to single-cell organisms

Sustainable fish farming is a necessity in Finland and broadly beyond to secure a supply of healthy protein and oil. The Finnish waters (The Baltic Sea and lakes) are shallow and therefore more prone to eutrophication than larger water areas such as the North Sea or the Atlantic. It is a known fact that natural waters, whether large or smaller, cannot satisfy the growing global demand for fish and other seafood. Aquaculture is the only way to reduce the pressure on wild fish stocks. Environmental concerns have motivated increased fish farming to protect natural fish populations from exhaustive fishing and to transition fish farming from natural waters and cage-based flow-through farms to land-based fish farms which circulate the water used in the grow tanks. RAS (recirculating aquaculture system) will become a more common practice to produce fish also in Finland. The amount of fish catch from natural waters is not seen to change in the future, the fish production will shift from fishery to farming.

A shift from cattle and pig to poultry farming increases the efficacy and sustainability of the meat production load but greatly increases the amount of feather byproduct. Unless featherless chicken varieties emerge in broiler chicken production, the increasing amount of feather will wait for sustainable value adding processing. Presently, feather is used to feed fur animals but more commonly converted to biogas, the digestate being used as fertilizer. Feather is practically pure protein with a global production of over 22 million tons per annum; in Finland ten to twenty thousand tons. Feather is, by definition, an interesting source of protein, but it will not be used for edible purposes in the near future due to its properties that support material and pet food rather than food use.

Insects and cell cultures have a great potential to replace meat as providers of high-quality protein. The production of both is resource efficient, sustainable and affordable. Many insects, such as crickets, black soldier flies or mealworms, to mention only a few, contain good-quality protein and fats for human nutrition. By employing technologies, insect protein ingredients can be produced without too much compromise regarding meat-like structure and taste. Single cell protein (SCP) production for feed or food is nothing new. Quorn™ is a meat substitute produced commercially from Fusarium fungus biomass for human food and animal feed. An emerging possibility is culturing meat and plant cells in controlled environments, i.e. bioreactors. Cellular agriculture will be one of the ways to produce food in the future.

5.3 SMART AND INTEGRATED CONCEPTS ARE PREREQUISITES FOR FAST TRANSITION TO SUSTAINABLE ENERGY SYSTEM

”Where are we going?” - drivers for future energy systems

Replacement of fossil fuels by renewable energy or other carbon-free energy sources is essential for achieving a low-carbon or even carbon-neutral energy system by 2050. Integration of an increasing share of variable renewable energy (VRE), e.g. solar and wind, in energy systems would require increased flexibility both in terms of energy systems and market designs. Nuclear, bioenergy, hydro power, and other renewable energy will still play an important role in future energy supply but their roles could be different. As an example, bioenergy would be more flexibly used in parallel with VRE and also act as an energy storage (see, e.g. the info box, p. 36).

In the package of “Clean Energy for all Europeans”[48] the European Commission states that consumers are active and central players in the energy markets of the future and consumers across the EU will in the future have a better choice of supply and the possibility to produce and sell their own electricity. In addition, the revised Renewable Energy Directive (RED2)[49], empowers consumers by enabling consumers to self-consume renewable electricity and feed the excess to the grid and also by opening access rights to local district heating and cooling systems in certain conditions. Thus, it can be expected that smart energy systems will enable more distributed generation and demand-side management supported by the ICT and automation.

However, if we only aim at decarbonizing the energy systems, we are most likely not able to maintain the temperature increase well below

Bio-CCS – enabling CO_2 removal from the atmosphere

Biomass utilizes significant amounts of atmospheric CO_2 during photosynthesis. This same CO_2 is released back into the atmosphere during conversion of biomass to energy. Capturing and permanently storing CO_2 originating from biomass enables a withdrawal of CO_2 from the atmosphere. This creates a carbon sink; so called negative CO_2 emissions, a climate mitigation tool that is predicted to be of increasing importance during this century. The pulp and paper industry has been identified by the International Energy Agency (IEA) as a potential sector for demonstration of industrial Bio-CCS. A recent study on Bio-CCS in the pulp and paper industry undertaken by VTT, in cooperation with IEAGHG, showed that if negative CO_2 emissions would be credited in emission allowance schemes, such as the EU ETS, the pulp and paper industry could create additional revenue from capturing and storing biogenic CO_2 emissions. For instance, a future negative emission credit of 20 €/t CO_2 higher than the break-even price of CCS would enable an additional profit of around 150 M€/a for a medium-size Kraft pulp mill (800,000 adt/a)[52]. VTT is now taking the Bio-CCS concept one step further by investigating potential and possibilities for the pulp and paper industry to become carbon sinks by developing CO_2-free pulping and to open bottlenecks that limit pulp production. Technologies include, among others, the utilization of captured CO_2 as feedstock in renewable fuel production and chemical production (Bio-CCU), use of the pre-calcination process in the lime-kiln and assessing the Bio-CO_2 value chains and business potential in circular economies.

2 °C, as agreed upon in the UN Paris Climate Agreement[50] and avoid the risk of abrupt climate change. Therefore, new technology, system, and market solutions are needed for achieving also "negative emissions", i.e. withdrawal of CO_2 from the atmosphere and by increasing carbon sinks in forests and soils. In the former case we produce bioenergy or bioproducts and capture CO_2 from flue or process gases. If CO_2 is permanently stored in deep underground formations, or permanently isolated from the atmosphere in other ways, we will have negative net emissions[51]. Another option is also the use of atmospheric CO_2 (direct air capture of CO_2 (i.e. DAC) or biogenic CO_2) as a raw material for fuels, materials, or chemicals[42]. Thus, it should be noted that CCU is not mitigating GHG emissions, if CO_2 is released back to atmosphere after a short period. However, if the use of fossil fuels is replaced by atmospheric CCU-based fuels or materials, then GHG emissions can be reduced if renewable energy input is used.

5.3.1 Changes in energy systems in the three alternative scenarios

The existing energy system in Finland is based on versatile energy sources, creating the opportunity for a resilient pathway to a low-carbon energy system. The characteristics of the energy system development in the three scenarios builds upon our assumptions on the national economy and demographics, development of new technologies and systems, and also on social change. Many of our decisions are still primarily based on costs but we also expect that cultural changes, values, acceptance, and other drivers of human behaviour could pave the way towards sustainable economies. Here, we have primarily concentrated on technical issues, including cost development, but as already described in the previous chapters, especially the BioEco scenario includes also assumptions about social change. The main characteristics of the scenarios considered are described in the Appendix and shortly described below.

In the CNS scenario we have assumed that the primary aim is to ensure a versatile energy mix, and thus the use of fossil fuels with carbon capture and storage in the long term is also included. In addition, in the CNS scenario, bioenergy with carbon capture and storage (Bio-CCS) proves to be a solution that has considerable potential in Finland due to the large forest and other biomass resources, which are used by forest industries and for bioenergy production. In contrast, in the BioEco scenario, we have assumed that fossil CCS will not be realized and also the assumed policies on strict sustainable criteria reduce the potential for Bio-CCS, but advanced uses of biomass and diversification of the renewable energy supply provide counterbalancing emission reductions.

The greatest difference in CNS and BioEco scenarios in energy lies in the assumptions related to the assumed cost development of VRE and the so-called power to gas and power to liquid concepts (see the info box NeoCarbon, p. 36). In the BioEco scenario we have expected very rapid learning rates and cost reductions for production of synthetic fuels (e.g. methane and methanol) from renewable electricity and CO_2. In addition, seasonal storage of VRE would also be possible, which would facilitate VRE integration even more.

Solutions for challenges in transition to a low-carbon energy system

Flexible Renewable Energy Solutions: Integrated Bioenergy Hybrids

Integrated bioenergy hybrids have recently been defined as a potential solution to bring flexibility to the energy system dominated by variable renewable energy (VRE) generation. Integrated bioenergy hybrid is defined as an energy conversion process that has at least two energy inputs, of which one is bioenergy. As the share of VRE supply continues to increase due to significant cost reductions, it raises an important question of how to most efficiently ensure the stability and reliability of the energy supply in low-GHG bases. Bioenergy is an easily storable source of renewable energy that can temporarily balance the energy supply and demand. A large number of commercial bioenergy solutions in heat, power and transport sectors are already available in the market place, and they are widely applied at various sizes, locations and applications. However, by integrating other energy resources into the same process, benefits in terms of resource-efficiency, costs and efficiency can be achieved. Most of the current hybrid systems are found in the heating sector, particularly on the household-scale, and high potential exists especially in district heating applications. In the power sector, bioenergy can have a strategic role as a flexible component in a VRE-dominated energy system; an example is chemical storage of electricity through hydrogen into biofuels, e.g. coupling of biogas or biomethane with hydrogen from a wind power plant. Also, solar energy-based biomass drying, through which solar energy is stored in the biomass for later use, is a potential field of application.

Neocarbon energy (P2G)

The operating principles and key components of a plan B energy system are very different from those of the current energy system. Plan B refers to the system designed with the assumption that nuclear power and fossil fuels with carbon capture and sequestration (CCS) would not be an option in our low-carbon energy pallet. These assumptions leave only solar and wind power alongside sustainable hydro and bioenergy in various forms as options in a low-carbon energy system. This is relevant now as solar and wind energy are becoming competitive and applied on a large scale.

The main technical barrier preventing societies from shifting from a fossil fuel-based energy system to a renewable energy system is the intermittent nature of solar and wind power. The problem of intermittency could be overcome by developing large-scale energy storage systems that are capable of responding to the electricity network consumption-production fluctuations on a sub-second, minute and hourly level and providing up to several weeks of energy storage on the country level.

The proposed solution for the energy storage problem is the production of synthetic natural gas (SNG), methane, from CO_2 and H_2 during periods of excess electricity production from solar and wind power. The expanding natural gas infrastructure provides nearly infinite storage capacity in the form of chemical energy, and can thereby provide heat, power, transportation and industrial sectors with renewable energy.

Solutions for decarbonizing transport sector

Combined production of transport fuels and heat

Large-scale fluidized-bed gasification systems have been recently employed in Finland for converting low-grade wood residues and waste fuels to fuel gas to replace fossil fuels in CHP power plants and in industrial kilns. This has created valuable industrial experience and confidence for more demanding syngas applications. However, the recently demonstrated BTL processes based on pressurized oxygen-blown gasifiers coupled with Fischer-Tropsch synthesis are too complex and require very large scales in order to achieve positive economics. This, in addition to technical uncertainties and availability risks have resulted in difficulties in financing the first-of-a-kind industrial plants. A significant penetration of 2G biofuels into the commercial fuel markets can only be achieved by creating new concepts, which are suitable to the smaller size range and have clearly lower capital and operational costs.

In the advanced process concept developed, biomass residues are gasified in a dual fluidized-bed gasification process, the raw gas is filtered, catalytically reformed and purified from sulfur compounds by zinc oxide-based sorbents. After polishing gas cleaning, the syngas is used in synthesis processes, which are also designed for the target size class of production (30–50 ktoe/a). Synthesis off-gases and by-product heat are used to generate heat and electricity, preferably at production units which are integrated into steam cycles of existing power plants.

Using pulping black liquor for the production of advanced transportation fuels

It is possible to convert part of the kraft pulp mill black liquor into an oil-like product called biocrude. VTT has been employing Hydrothermal Liquefaction (HTL) of black liquor to achieve an optimal level of energy recovery into biocrude. Although the biocrude may be used as a fuel oil, its further upgrading into transportation fuels is considered the ultimate goal for this biofuel production pathway. In the process, up to 75% of the energy content of black liquor can be extracted as an oil-like product under suitable process conditions. When co-processing the upgraded black liquor-based biocrude with vacuum gas oil the target is to produce gasoline hybrid fuels of standard yields and quality.

A new route to transportation fuels from forest residue and other biomasses – a result of Finnish American R&D co-operation

VTT and PNNL (Pacific Northwest National Laboratories) have produced transportation fuel from Finnish forest residue using a cost-effective bio-oil upgrading concept. Using this new production concept low-cost liquid biofuels and chemicals can be manufactured with 60% energy efficiency from biomass feed energy content to a final product. In the process concept, bio-oil is produced using the patented VTT integrated fast pyrolysis technology, and the crude oil is transported to an oil refinery to be upgraded potentially with mineral oils. Production capacity of this concept can be increased stage-wise due to modularity of units, which lowers the risk for the investor. The efficiency and economic benefits have already earlier been proven with European partners and now the ambition of this Finnish-American co-operation is to find out solutions for the biggest challenges in upgrading. Globally, Finland is the forerunner in commercializing fast pyrolysis technology for wood. The world first commercial integrated fast pyrolysis plant is in operation in Joensuu by the Fortum corporation with the production capacity of the plant being 50,000 tons of bio-oil a year.

6. Reaching the low-carbon and climate and energy policy targets

With respect to the climate policy targets, both of the low-carbon scenarios reach deep reductions in greenhouse gas emissions. As the targets for greenhouse gas emission reductions were set on the EU level, the reductions are not evenly distributed between member states, but allocated according to cost-efficiency. The results indicate that with a wide-scale utilization of Bio-CCS, as in the CNS scenario, Finland would have a higher cost-efficient emissions reduction potential than the average over the EU, but in the BioEco scenario deep reductions become somewhat more expensive in Finland, due to the reduced sustainable bioenergy potential. Looking at the scale of Bio-CCS applications in the CNS scenario, which amounts to over 12 Mt(CO_2), the results thus give a strong indication that if CO_2 storage services become commercially available, Bio-CCS technologies could offer Finland considerable business opportunities both for the energy technology industry and for the energy sector itself, through the emission trading system.

Nonetheless, as the total reduction of greenhouse gas emissions is nearly 80%, also in the BioEco case, both scenarios are good bases for a low-carbon economy for Finland (see Figure 9)[53]. Moreover, in the BioEco scenario, future Finland can realize an economic boost with a much larger production of high-value materials

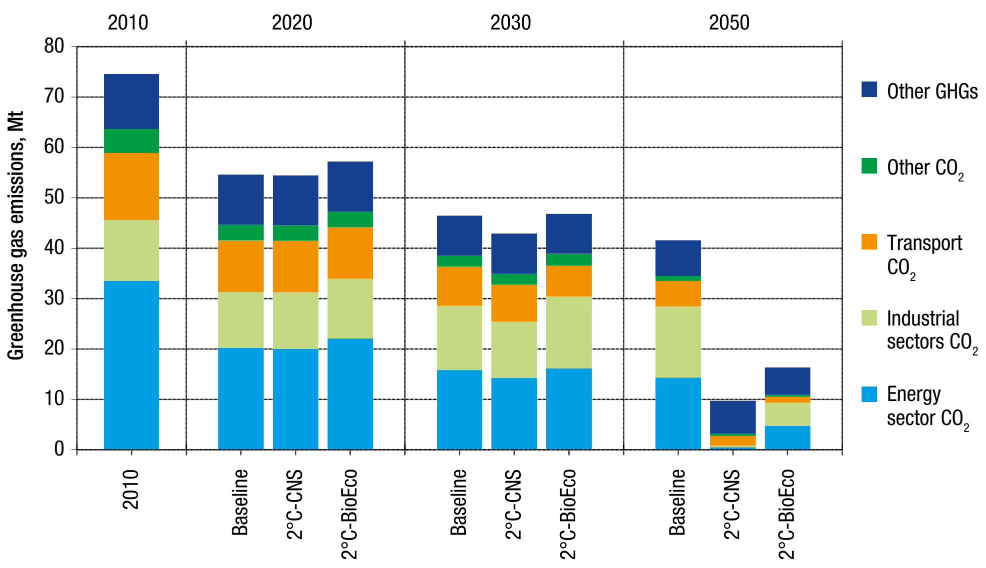


Figure 9. Development of greenhouse gas emissions in Finland in the scenarios[5,6,7].

from sustainable resources, contributing to new businesses, employment and welfare growth.

Within electricity generation, the share of renewable energy will increase highly in both of the low-carbon futures, comprising close to 80% of the total electricity supply. Nuclear power would still provide base load power at roughly the same level as in 2015, but all the remaining production would be almost exclusively based on renewable sources. With the cost estimates used[54,55], CCS for fossil fuel power would not appear to have any notable competitive position in Finland, even in the CNS scenario. Wind power generation reaches the level of 21–23 TWh, but solar power would also catch up with similar or even higher production levels by 2050 (see Figure 10).

In particular, solar power utilization is boosted by energy storage and power to gas and liquid systems in the sustainable bioeconomy future. In total, solar power production reaches 34 TWh in 2050, of which a considerable proportion is indeed used for synfuel production. In both of the low-carbon scenarios, the investment costs of utility-scale solar photovoltaic systems were assumed to decrease to around 350 €/kW and the costs of rooftop photovoltaic systems to 600–700 €/kW by 2050. This means about 60% further cost reductions in addition to the deep cost reductions experienced in 2010–2016.

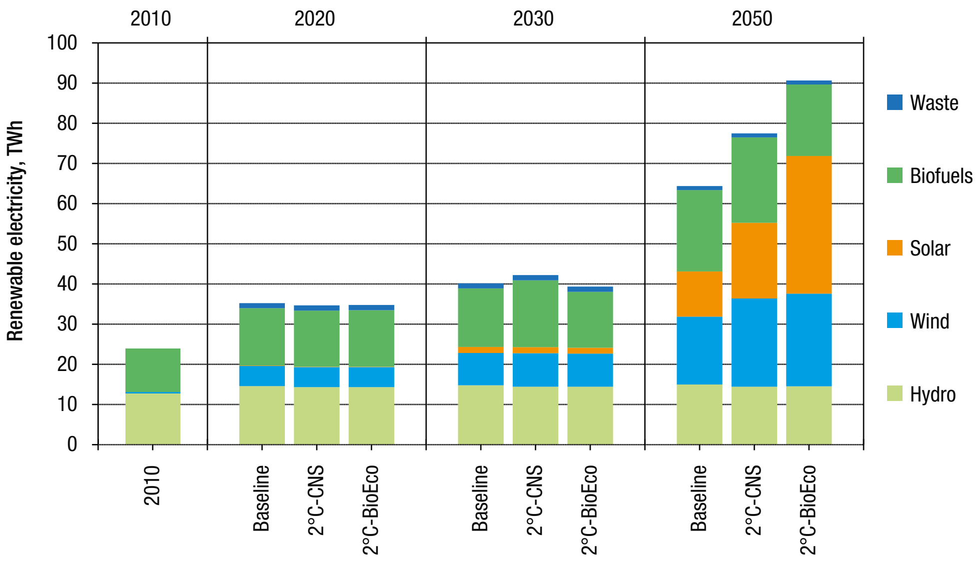


Figure 10. Development of renewable electricity production in Finland in the scenarios[5,6,7].

According to the scenario results, by 2050 solar panels will be installed extensively on residential and commercial buildings, such that the currently estimated potentials are more or less fully used. In the BioEco scenario, utility-scale solar power would also become prominent in Finland, for utilizing solar energy to a notable extent and also for producing carbon-neutral fuels for use across all seasons. The total contribution of renewable energy from total primary energy supply is roughly at the same level in all three scenarios (Figure 11). While in the Baseline and CNS scenarios the supply of renewable energy remains highly on wood biomass, in the BioEco scenario it becomes more diversified. It is also noteworthy that in the BioEco scenario the electricity demand increases from the current approximately 80 TWh to 130 TWh due to strong electrification in 2050, while in both Baseline and CNS scenarios the demand is about 100 TWh.

In the low-carbon scenarios, district heat generation will efficiently utilize bioenergy, ambient and waste heat sources with large-scale heat pumps, and solar heat. The role of fossil fuels is reduced close to zero, e.g. mainly to peak uses, and is at a minimal level by 2050. But through advanced bioenergy technologies, thermal CHP generation is still able to maintain a considerable share in total electricity generation in 2050 (8–9 TWh), in both scenarios.

Fuel conversion and storage

Power to gas and liquid fuels and energy storage technologies have an important role in the BioEco scenario for stabilizing the electricity grid. These technologies include hydrogen boosted syngas production, reversible dual-mode hydrogen fuel cells (RSOFC), and, according to the results, we would even see the emergence of a methanol synthesis process in commercial scale application, which is based on direct air capture (DAC) of CO_2. The synthetic carbon-neutral fuels are used for both heavy-duty transports and industrial processes in the BioEco scenario.

Production of liquid biofuels for the transport sector becomes particularly prominent in the CNS scenario, but remains important for heavy-duty transport also in the BioEco scenario, despite the much narrower resource base fulfilling sustainability criteria. The technologies are mostly 2nd generation Fischer-Tropsch (FT) processes, with hydrogen boosting enhancing resource sufficiency, especially in the BioEco

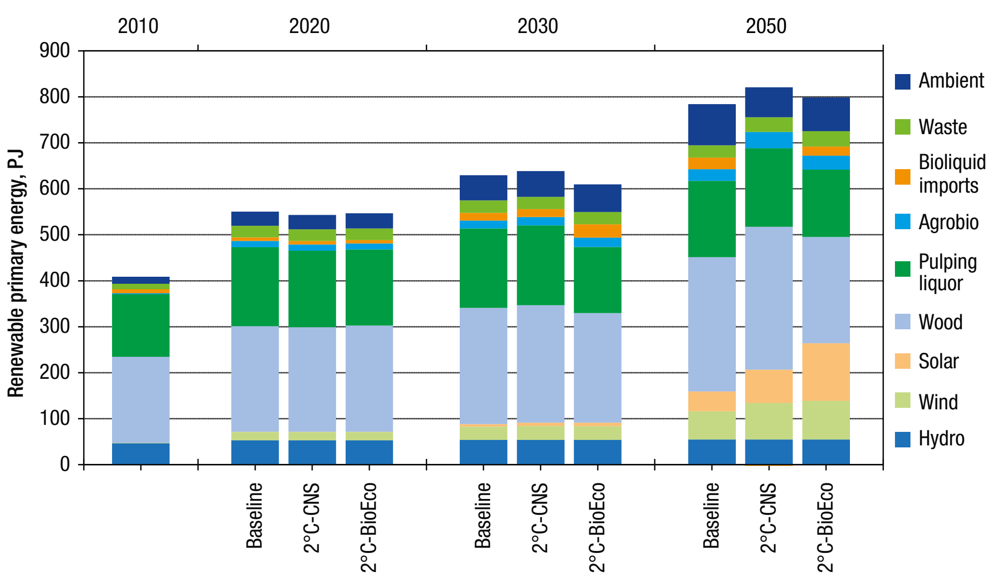


Figure 11. Development of renewable primary energy in Finland in the scenarios[5,6,7].

scenario[56]. However, in the CNS scenario some of the hydrogen-boosted technologies also prove to become commercially viable, for example the hydrothermal black liquor to biodiesel conversion process, due to the black liquor energy surplus at pulping plants becoming increasingly large in the CNS case.

In addition, biogas production from manure and grass sod would integrate the agriculture sector more closely into the energy supply system in the BioEco scenario, where the biogas production from agricultural by-products reaches about 3.5 TWh in 2050.

Technologies providing the necessary energy storage capability in the BioEco scenario include e.g. CAES systems, supercapacitors, and seasonal hydrogen and methane storage facilities, and are supported by the power to gas and liquid technologies. The potential of utilizing batteries of electric cars as a balancing storage was not taken into account in the modelling.

Transportation

Electrification of light-duty road transports is extensive in both of the low-carbon scenarios, and also seems almost inevitable for achieving a low-carbon economy, due to the scarceness of sustainable bioenergy as a replacement of mineral oil-based transport fuels. However, in principle, large-scale production of synthetic transport fuels from either fossil fuels with CCS or via DAC systems could provide an alternative low-carbon pathway to the transport system.

In the CNS scenario the Finnish transport system remains more heavily dependent on liquid fuels, as the sustainable domestic bioenergy resource base is sufficient for supporting it. However, with a notable contribution from hybrid vehicles, electric cars gain a market share of 75% even in the CNS scenario by 2050, while in the BioEco scenario it reaches 80% and consists primarily of full electric vehicles. Fuel cell vehicles will cover an additional 10–15% of the passenger car fleet in 2050.

By 2050, biofuels are thus no longer used for light-duty vehicles in the BioEco scenario. Even buses will become largely electrified with plug-in hybrid systems. However, heavy-duty road and ship transports as well as air transport continue requiring substantial amounts of biofuels or carbon-neutral synthetic fuels even in the BioEco scenario.

7. Economy in the 2050 scenarios

To analyse the impacts of value-added production in the BioEco scenario on the national economy, we have used the FINAGE model of the Finnish economy to simulate three scenarios for the development of the economy to 2050. Figure 12 below shows the effects of the CNS and BioEco scenarios on GDP as decomposed to contributions by each of the elements of the supply side of the economy. This decomposition encompasses the change in the factors of production – labour and capital – and technological change – changes factor productivity and material efficiency. It also reports the effect of changes to indirect tax revenue – by definition a part of GDP. For each of the scenarios, the figure depicts the sum of changes at the sectoral level as aggregated, economy-level contributions to a deviation from the baseline.

There is a remarkable difference between the CNS and BioEco scenarios: in the former, policies and technology after 2030 focus narrowly on cutting emissions, whereas in the latter, several sectors of the economy introduce advanced new products and business models that also entail

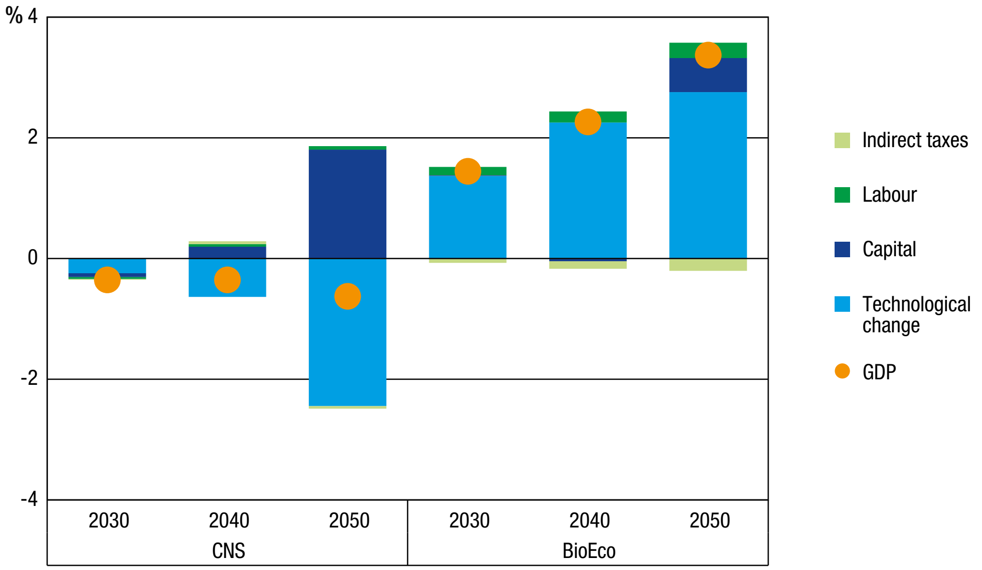


Figure 12. Supply side contributions to GDP, percentage points from Baseline.

more energy and material-efficient production. In the CNS scenario, the technologies are also more capital intensive, reflecting a tendency to substitute increasingly more expensive energy with capital, and thus the contribution of capital is positive and very large in the CNS scenario. In the BioEco scenario, the role of energy is relatively more marginalized, and the growth of the economy is relatively more de-coupled from the use of energy, materials, and capital. In the BioEco scenario, economic growth stems mostly from the contribution of technology, generating growth from more efficient and new uses of materials and energy, whereas in the CNS scenario, technology reflects the rising relative prices of energy and materials. Thus, the effect in growth is actually negative for the CNS scenario and positive for the BioEco scenario.

Figure 13 below shows the effects of the CNS and BioEco scenarios on domestic value added decomposed to contributions of value added and technological change by industry. The figure shows that, by and large, the CNS scenario cuts the contribution to GDP growth of all other

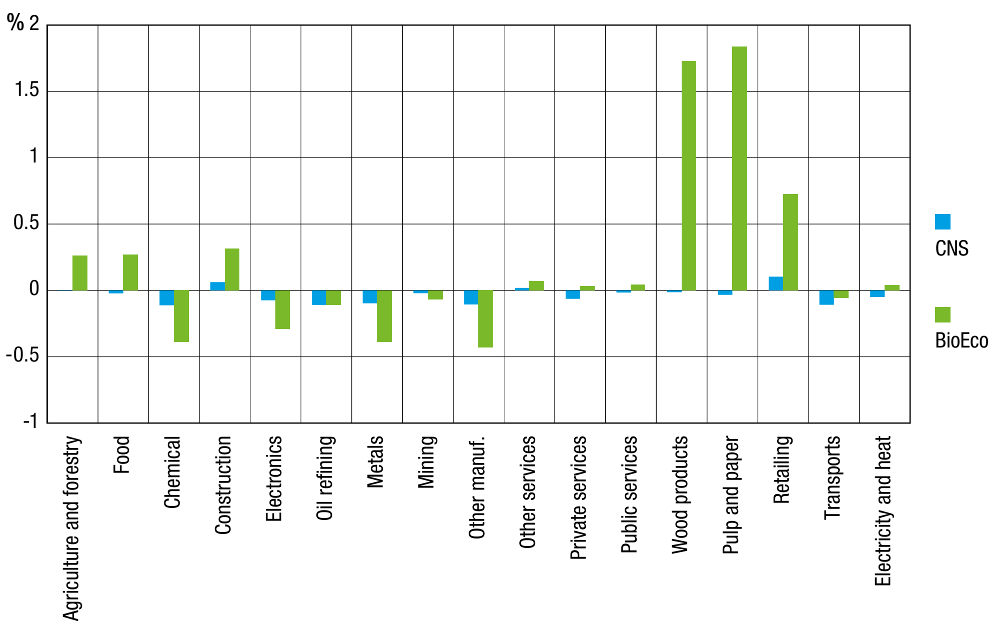


Figure 13. Industry contributions to GDP change, percentage points from Baseline in 2050.

sectors except construction and retailing, whose contribution in the figure is positive (i.e. greater than in Baseline scenario). These sectors benefit from the heavy investment in energy saving characterizing the CNS scenario, because their inputs are needed in the investment process, but for all other sectors the choices in the CNS scenario impose additional costs that erode their growth. In the BioEco scenario, in contrast, several sectors benefit from the introduction of new technologies and products, as well as new business models. The scenario introduces these in the forest and wood product industries, as well as the agro-food sectors. In these sectors, both factor productivity and material efficiency gain and thus the growth contribution of technology and value added. Construction and retailing also benefit, but the largest contributions stem from the wood product and forest industries.

Figure 14 shows the contributions to GDP change of demand side components of GDP. The difference between the CNS and BioEco scenarios is again striking. In the former, rising domestic costs erode the price competitiveness of Finnish goods, leading to a fall in exports. Investment tends to pull GDP growth with it, but not enough to off-set the negative contribution of exports. Furthermore, a large share of investment goods consists of imports, whose growth is reflected by the negative contribution of imports to GDP compared to Baseline. In the BioEco scenario, new products create new exports, which are also sustained by the increased energy and material efficiency of the economy. This also improves the purchasing power of the consumers, and thus consumption also contributes to GDP growth more markedly than in the CNS scenario.

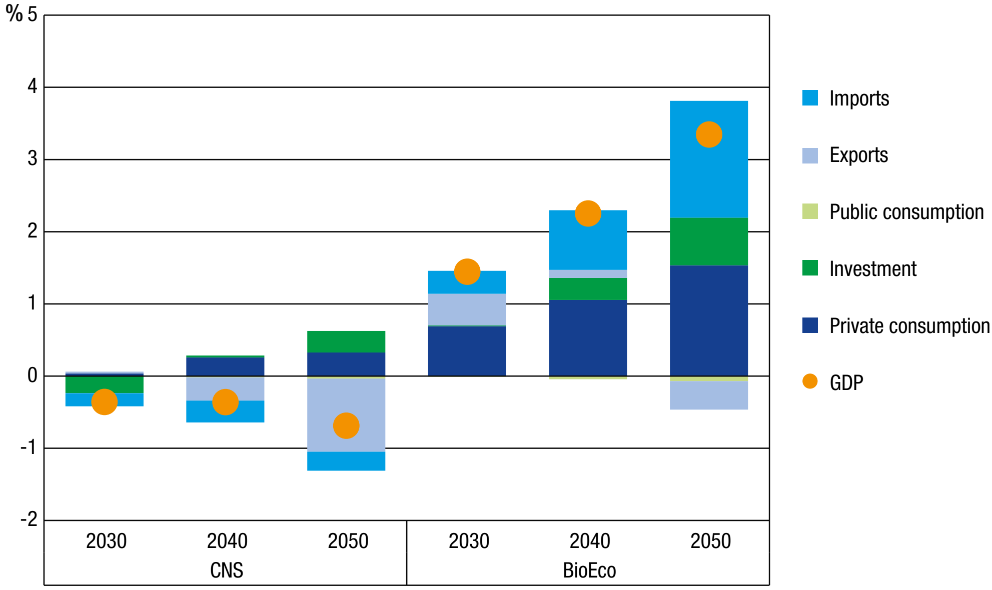


Figure 14. Demand-side contributions to GDP, percentage points from Baseline.

8. Discussion

Finland is recognized as a leading country in bioeconomy. The results show that there is still a lot of untapped potential in utilizing our forest and agricultural resources. It must be also noted that these potentials exclude any technology or service business that may grow alongside the development of new products. In addition, we need to ensure that natural diversity and the environment are protected.

Finland still has an advantage compared to many countries in developing the bioeconomy. On top of our natural resources, we have an industrial base already mobilizing and refining the resources, and above all, we have the intellectual capacity to develop new, innovative products and services. To maintain this advantage we need make sure that we continue to invest in all four strategic goals identified in Finland's Bioeconomy strategy:

1. Creating a competitive operating environment for bioeconomy growth
2. New business by means of risk financing, bold experiments and the crossing of sectoral boundaries
3. Developing education, training and research for a strong bioeconomy competence base
4. Securing availability and sustainability of biomasses and well-functioning raw material markets.

The Bioeconomy strategy has outlined actions that are needed to achieve the aforementioned goals, but it needs to be emphasized that bioeconomy development is a long-term process, and entering of new products into markets is always based on years or even decades of intensive research and development. Hence, it is of paramount importance to invest in all stages of innovation from education all the way

to commercialization, otherwise we will lose our innovation capacity and let others reap the benefits of an advanced bioeconomy. In addition, collaboration with research, companies, and other stakeholders is critical in creating the new ecosystems in bioeconomy.

Especially forest – but also agricultural products industries – are going through substantial transformation due to major changes in global markets driven by demographic changes, population growth and increased GDP, especially in Asia, in addition to climate change and natural resource concerns. At the same time, new applications and uses of wood and agricultural raw materials and their components are developed. It is evident that well-positioned industries and companies can expect demand to grow for those products that enhance sustainable development of our environment and well-being of people. As an example, fibre-based products for tissue papers, packaging, and textiles will especially grow in Asia.

The results of this report affirm the views that the current industrial production systems in Finland have the flexibility to bring more added value. The immediate benefit comes from further processing and refining of agricultural and forestry raw materials and their intermediate products, like cellulose, or side streams into higher-value products. This is where small and medium enterprises could have a significant role. Together with the bigger producers and research partners, they are already starting to form business and innovation ecosystems that will develop and bring the new products to the markets. At the same time, we are witnessing the manufacturing industry transitioning from the era of mass production into the era of smart production, where physical production merges with the opportunities created by digitalization. This change will take place in the bio-based sectors, too. What new business this will bring is still unknown, but we cannot let this opportunity slip through our hands, especially when it combines the very strengths and capabilities of Finland.

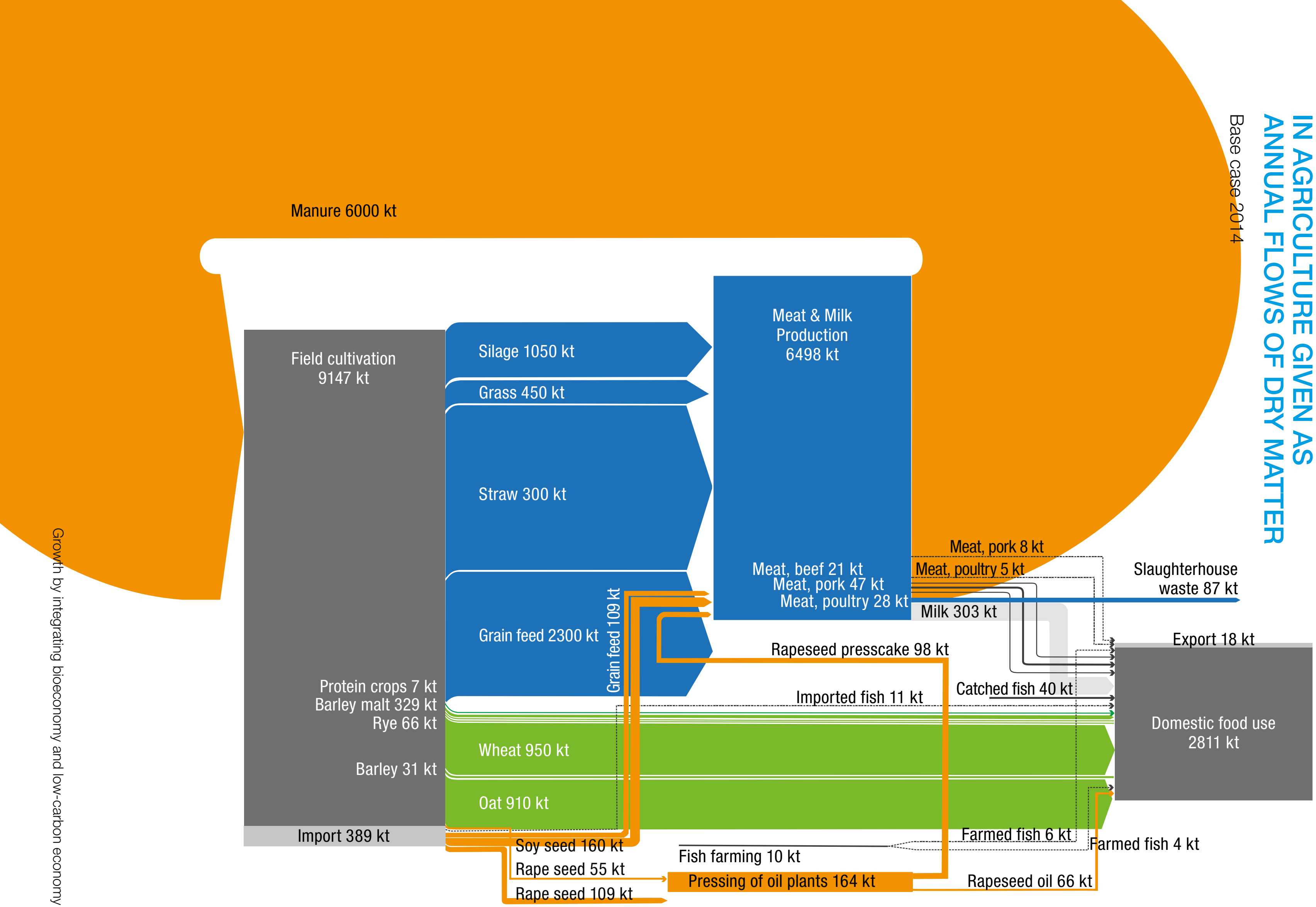
APPENDIX 1: MAIN CHARACTERISTICS OF THE SCENARIOS CONSIDERED

Table 1. Main characteristics of the scenarios considered.

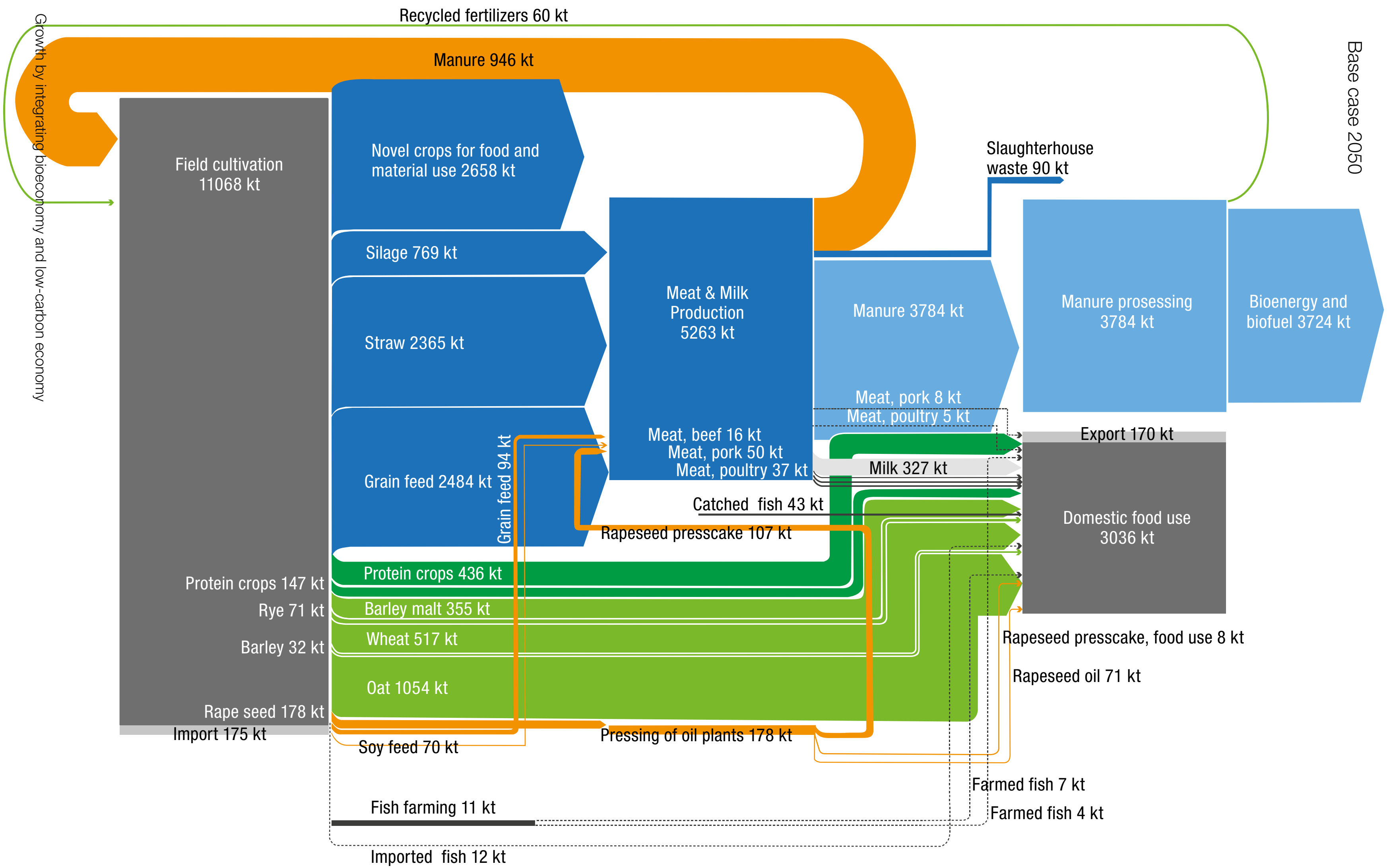
Characteristic	Subject	Baseline	CNS	BioEco
Climate policies	General	EU 2030 policies EU -40% in GHG	Global 2°C EU -80% in GHG	Global 2°C EU -80% in GHG
	Bioenergy	Current policies	Current policies	Strict sustainability criteria for biomass
Energy sector	Power and heat	Baseline technology development	Rapid technology development	Rapid development boosted by storage, PTF and CCU
	CCS / Bio-CCS / CCU / DAC	Only limited role under the EU 2030 policies	CCS commercially viable in energy sector and industry	CCS limited to fuel conversion and industry, CCU/DAC for power-to-fuels
Transportation	Energy sources	Biofuels in focus	Biofuels and electrification	Electrification and synfuels
	Technology	Conventional development	Rapid development	Rapid development
Agriculture	Crop production	5.7 Mt (2050)	5.7 Mt (2050)	5.2 Mt (2050)
	Meat production	0.43 Mt (2050)	0.43 Mt (2050)	0.23 Mt (2050)
	New products	0 B€ (2050)	0 B€ (2050)	1 B€ (2050)
	Foodstuff-VA	4.6 B€ (2050)	4.6 B€ (2050)	6.0 B€ (2050)
Chemical wood processing	Chemical pulp	8.4 Mt (2050)	8.6 Mt (2050)	9.5 Mt (2050)
	Papers and boards	8.6 Mt (2050)	8.6 Mt (2050)	8.0 Mt (2050)
	New products	0.1 Mt (2050)	0.2 Mt (2050)	4.2 Mt (2050)
	Value added	5 B€ (2050)	5 B€ (2050)	12 B€ (2050)
Mechanical wood processing	Sawnwood	13.5 Mm^3 (2050)	13.5 Mm^3 (2050)	7.8 Mm^3 (2050)
	New products	1.9 Mm^3 (2050)	1.9 Mm^3 (2050)	10.2 Mm^3 (2050)
	Value added	2 B€	2 B€	6 B€

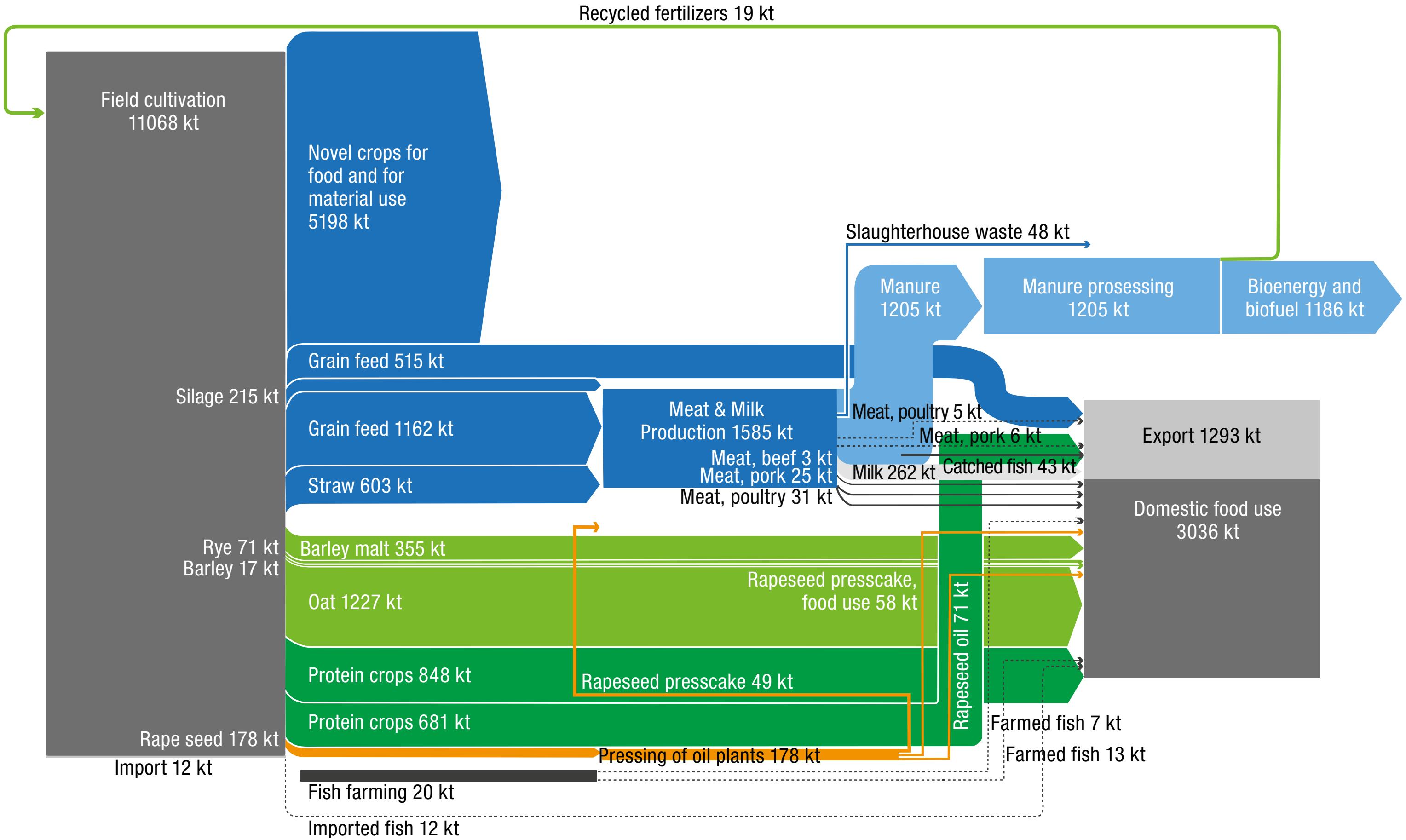
APPENDIX 2: BIOMASS FLOWS IN AGRICULTURE GIVEN AS ANNUAL FLOWS OF DRY MATTER

Base case 2014



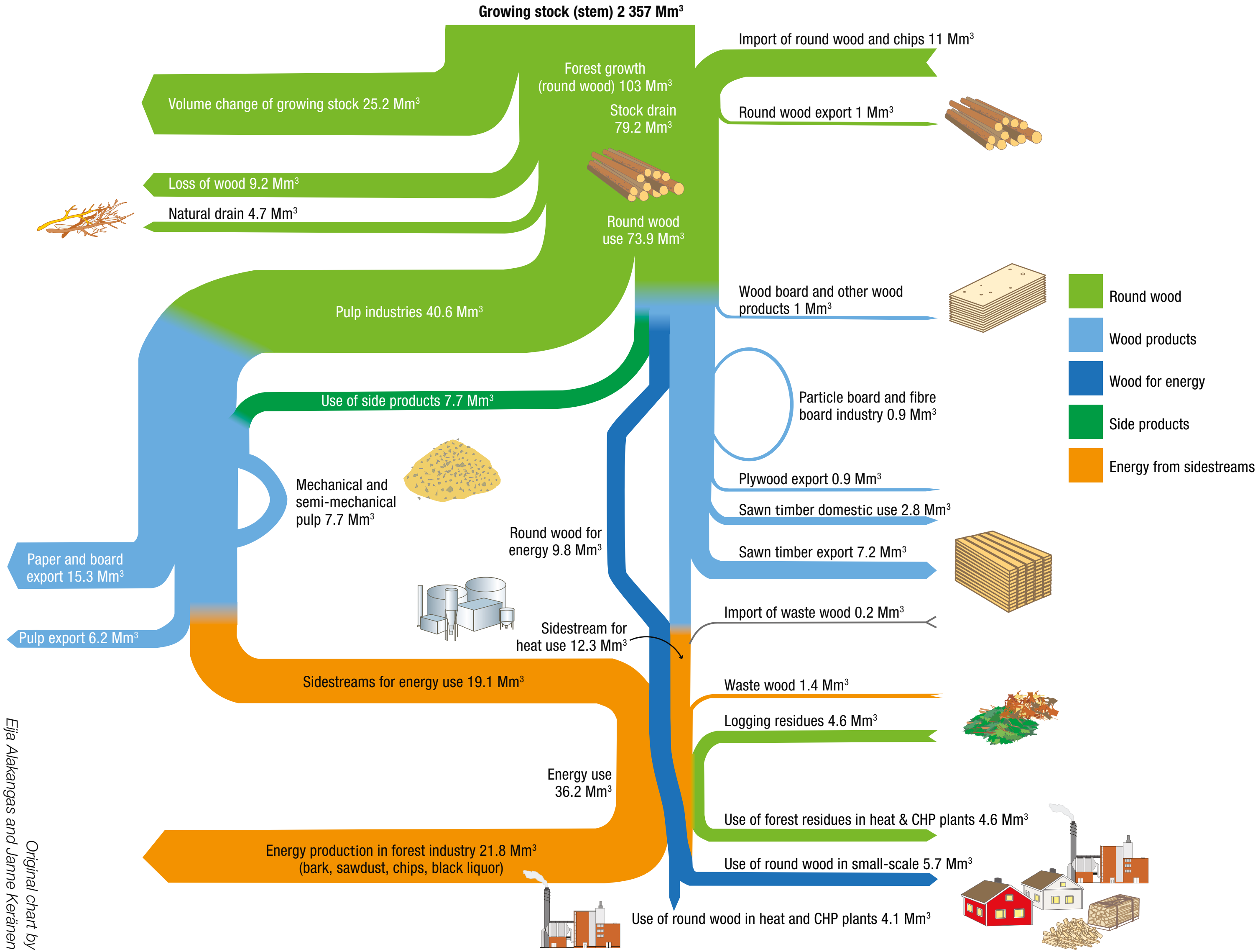
Base case 2050




Recycled fertilizers 19 kt
Field cultivation 11068 kt
Novel crops for food and for material use 5198 kt
Slaughterhouse waste 48 kt
Manure 1205 kt
Manure prosessing 1205 kt
Bioenergy and biofuel 1186 kt
Grain feed 515 kt
Silage 215 kt
Grain feed 1162 kt
Meat & Milk Production 1585 kt
Meat, beef 3 kt
Meat, pork 25 kt
Meat, poultry 31 kt
Straw 603 kt
Meat, poultry 5 kt
Meat, pork 6 kt
Milk 262 kt
Catched fish 43 kt
Export 1293 kt
Domestic food use 3036 kt
Rye 71 kt
Barley 17 kt
Barley malt 355 kt
Oat 1227 kt
Rapeseed presscake, food use 58 kt
Rapeseed oil 71 kt
Protein crops 848 kt
Rapeseed presscake 49 kt
Protein crops 681 kt
Farmed fish 7 kt
Farmed fish 13 kt
Rape seed 178 kt
Import 12 kt
Pressing of oil plants 178 kt
Fish farming 20 kt
Imported fish 12 kt

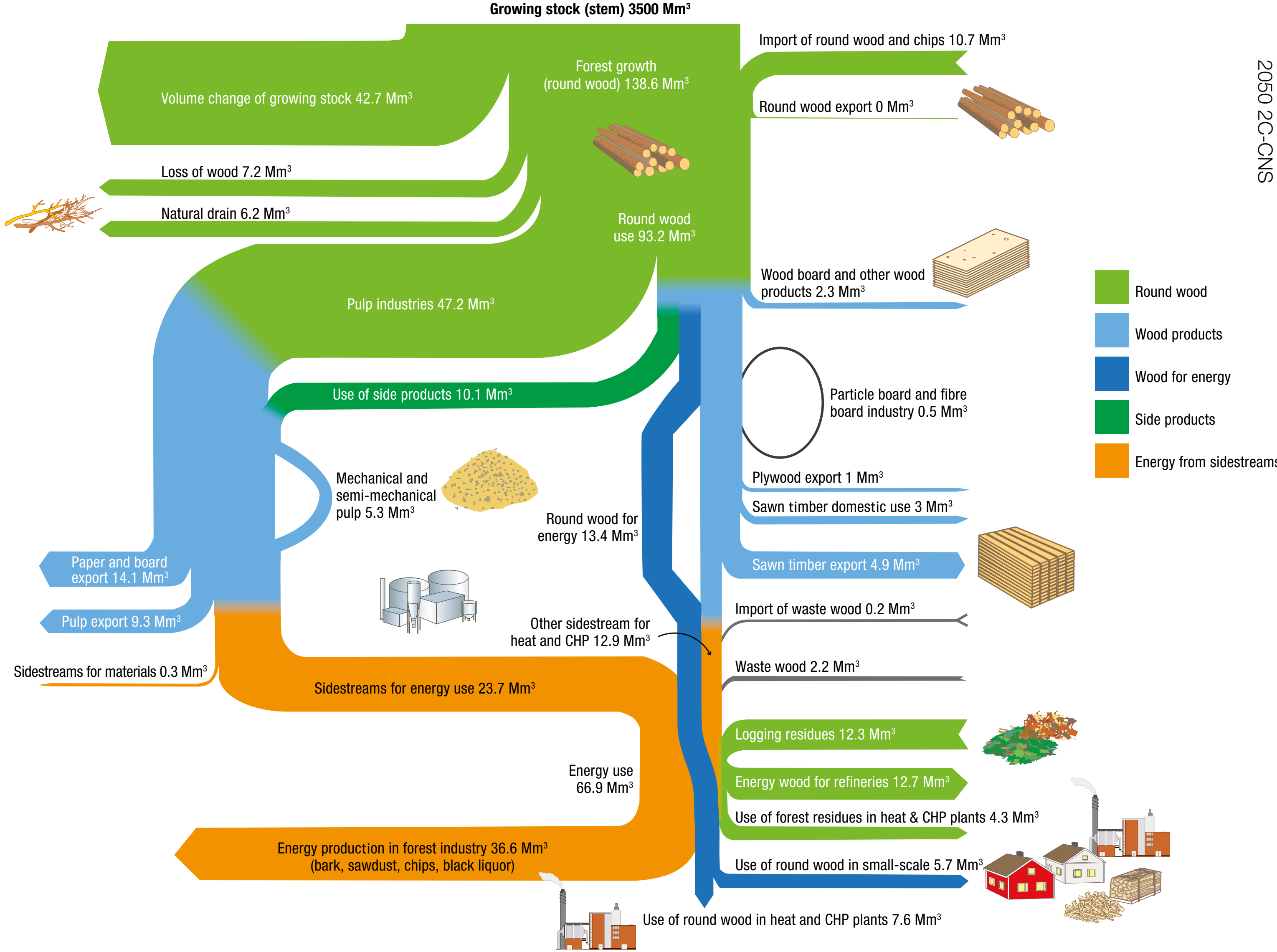
APPENDIX 3: FOREST-BASED BIOMASS FLOWS

Wood flows in Finland, 2013.
Modified from Alakangas et al. 2018[57]

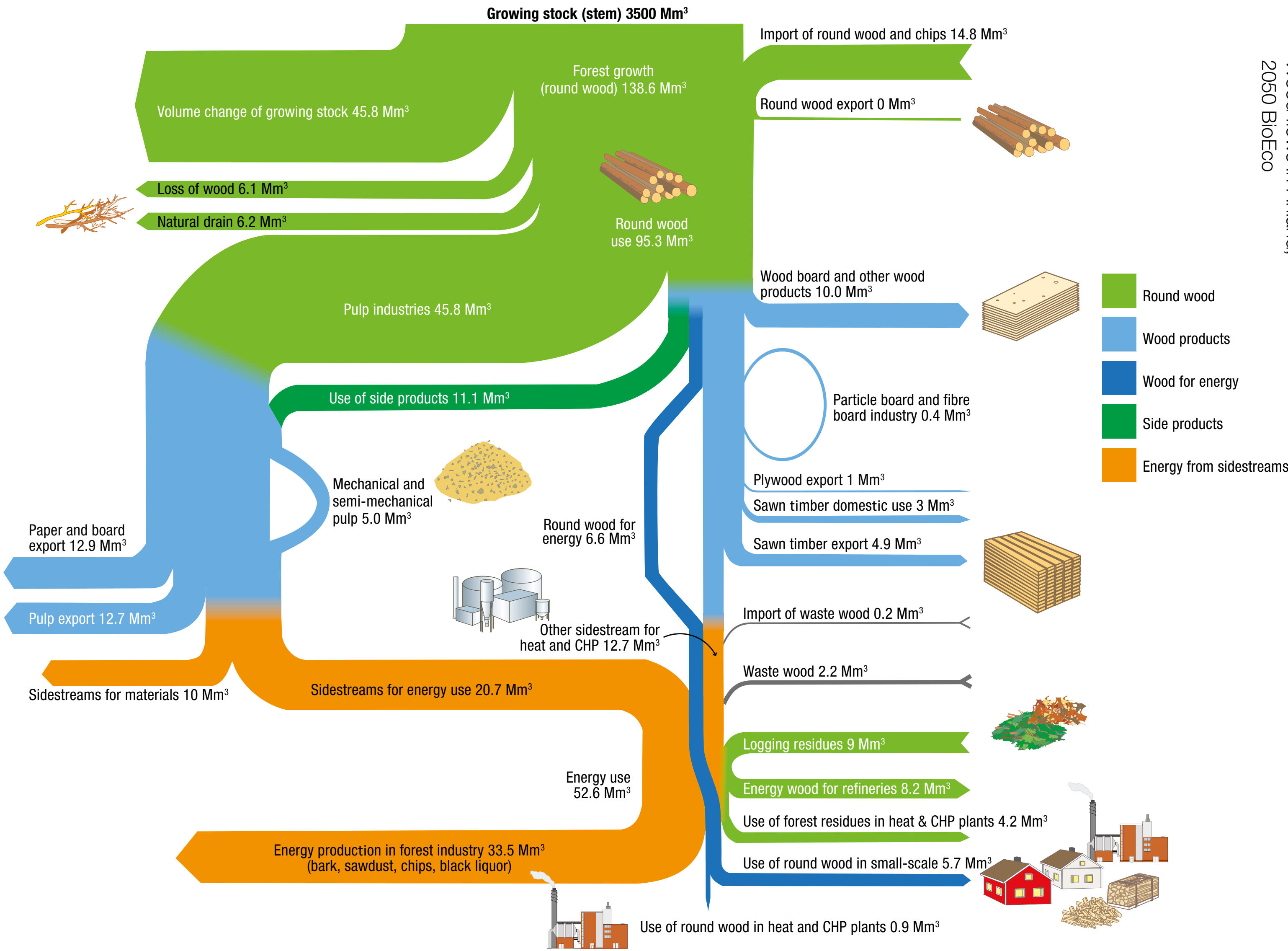


Original chart by Eija Alakangas and Janne Keränen

Wood flows in Finland, 2050 2C-CNS



Wood flows in Finland, 2050 BioEco



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Series title and number
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Title	**Growth by integrating bioeconomy and low-carbon economy Scenarios for Finland until 2050**
Authors	Antti Arasto, Tiina Koljonen & Lassi Similä (eds.)
Abstract	Bioeconomy refers to the various sectors of primary production, such us agriculture, forests and fisheries, and industrial sectors, which transform bio-resources to bio-products. Industrial sectors in bioeconomy cover food and feed industries, cellulose, paper and wood processing industries, bio-refineries, chemical and energy industries, and also the marine and maritime sectors. In addition, bioeconomy includes ecosystem services of nature, such as recreation and wellbeing as well as tourism. In this report, the primary focus is to analyse how to achieve full bioeconomy potential and bridge the on-going research to industrial implementation. In the analysis, we have mainly focused on forestry and forest industries, agriculture and food industries, as well as on bioenergy and biofuels. The aim has been to illustrate effective bioeconomy pathways and the impacts of accelerated R&D and related investments in bioeconomy on Finland's welfare and greenhouse gas mitigation. The analysis is based on views and synthesis of a large group of VTT's experts in the fields of forest and food industries, biomaterials, clean energy, and scenario modelling.
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