REPORT OF THE FINNISH FOREST BIOECONOMY SCIENCE PANEL 1/2024

From timber to medicine

Value added for the forest sector through broadening the product portfolio

Monika Österberg, Markku Karjalainen, Jussi Lintunen, Tekla Tammelin, Antti Asikainen, Esa Vakkilainen, Ritva Toivonen, Pasi Virta, Alexander Henn, Emmi-Maria Nuutinen, Johanna Kohl, Jukka Hassinen

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Abstract

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Forests are the foundation of Finland's diverse well-being. The forest industry is one of the largest industrial sectors in Finland and plays an important role in Finland's national economy. Finland's bioeconomy strategy has set a target of doubling the value added of the bioeconomy by 2035 without compromising biodiversity and climate objectives. However, achieving all forest-related targets is difficult, and choices must be made. To support these choices, research-based analyses are needed to find an optimal balance between forest use, conservation and climate objectives.

A discussion paper on the future of the forest sector published by the Natural Resources Institute Finland (Luke) in 2023 concluded that Finland has the potential to multiply forest-based value added, provided that the business environment can be made attractive for investments by domestic and international companies.

In this report of the Finnish Forest Bioeconomy Science Panel, we continue this discussion. We look into the potential future product portfolio of the forest sector and the value added it can generate. The products considered have been divided into upgrades of existing solutions and new innovations. The new innovations include, for example, flexible packaging, product groups based on advanced specialty fibres and a broad range of lignin products.

It is evident that a significant increase in forest harvesting is not sustainable. Thus, in the report we consider a scenario where value is added without increasing harvest volumes.

According to this report, the key strategies for enhancing the value added of the forest sector include extending value chains in Finland and using side streams more effectively. An impactful approach to value addition in the foreseeable future involves advanced processing of timber into cross-laminated timber (CLT) or laminated veneer lumber (LVL), which could replace concrete in the construction of apartment building frames. In the future, achieving significant value added requires the commercialisation of new material innovations in Finland. For example, if a quarter of the exported pulp (1,000 kt) were refined into, for example, nanocellulose, textile fibres, special packaging and barrier materials, a value added of €3 billion could be achieved. The extensive processing of lignin into various products could lead to a value added of €1.5 billion. In this scenario, the total value added would increase by more than 80% compared to 2019 levels. This increase is significant, although not sufficient to double the value added.

Substantial investments are essential to transform the existing product portfolio towards higher value-added products. Concurrently, investments in research and education are imperative. Finland must cultivate an operating environment that is appealing for both investments and skilled labour. While this report primarily focuses on economic considerations, it is crucial to acknowledge that forest-related choices are impacted by biodiversity and climate objectives. Thus, a holistic approach is necessary, integrating climate and restoration measures, as well as the advancement of the bioeconomy, to ensure that actions contribute optimally to all objectives.

The aim of this report is to lay the ground for future scenario analyses. The figures and estimates herein are based on a number of assumptions; therefore, the findings should be regarded as indicative. Nevertheless, the calculations have been extended to the sectoral and national economy levels, aiming to provide a more comprehensive estimate of the economic significance of the new products and their production. As innovations progress and data on manufacturing costs and sales market prices emerge, these estimates can be further refined for greater accuracy.

Policy recommendation of the Finnish Forest Bioeconomy Science Panel:

- The bio-based industry has the potential to accelerate economic development in the European Union. EU policy should steer research and investments towards high value added bio-based industries. Uncertainty about the conditions to use forests in the EU, for example, is eroding the investment climate. A key factor contributing to uncertainty is the proliferation of EU regulation related to forests, with more than 70 fluctuating policy measures affecting forests.
- Finland needs to become a more attractive environment for entrepreneurs and international talent. It is important that our university-educated masters, engineers, and doctorates find employment in Finland and integrate into Finnish society.
- To support bio-based material innovations, funding is needed for applied multidisciplinary development to ensure, among other things, the technical and financial potential, sustainability and performance of new materials in different applications.
- Wood should be used to make long-lasting and recyclable products that serve as carbon storage. Wood-based solutions can replace products with a higher carbon footprint than wood products, particularly in the construction sector. Wood and wood-based solutions should be integrated into education, industrial building frameworks and the policies that govern them.
- Forests are more than a material bank for the bioeconomy. Decision-makers need to reconcile the sometimes-contradictory objectives of forest use, such as economic growth, climate, biodiversity and recreation.

Keywords: bioeconomy, forest industry, value added, lignin, nanocellulose, further processing, wood construction, wood products

Contents

1. Introduction

Forests are Finland's key renewable natural resources in terms of well-being, the economy and climate. Forest assets are largely based on growing wood biomass and using it as raw material, processed products, and energy. The goal of the National Bioeconomy Strategy "Sustainably towards higher value added" (Finnish Government 2022) is to double the amount of value added by 2035 compared to the 2019 level. This doubling is to be ecologically, socially, and financially sustainable, also taking into account the commitment to becoming carbon neutral by 2035 as defined in the national Climate Act. The value added generated by the forest industry has been negatively affected in the 2000s by the decrease in demand for paper and its production (Figure 1). As a result, a growing proportion of Finnish pulp is exported without additional processing.

The global downturn in recent years, combined with geopolitical tensions, has significantly impacted the operating environment in the forest sector. The sanctions imposed on Russia following its invasion of Ukraine in 2022 halted wood imports from Russia which was expected to increase the harvesting of domestic wood. However, demand for forest industry products has significantly fallen due to such factors as rising inflation and interest rates, reducing production volumes in the industry as a whole in Finland (Finnish Forest Industries Federation 2024).

Despite the recent downturn, it is obvious that any significant increase in felling volumes in Finnish forests is not sustainable, and alternative means are required to create value added. This report of the Finnish Forest Bioeconomy Science Panel exlores innovations that, while still not being on a production scale, can however increase the value of forest sector production in Finland in the mid and long term. This report also presents possible actions, policies, as well as research, development and innovation (RDI) activities that can speed up these innovations on their way from laboratories to production lines and plants, as well as various risks and restrictions associated with different scenarios.

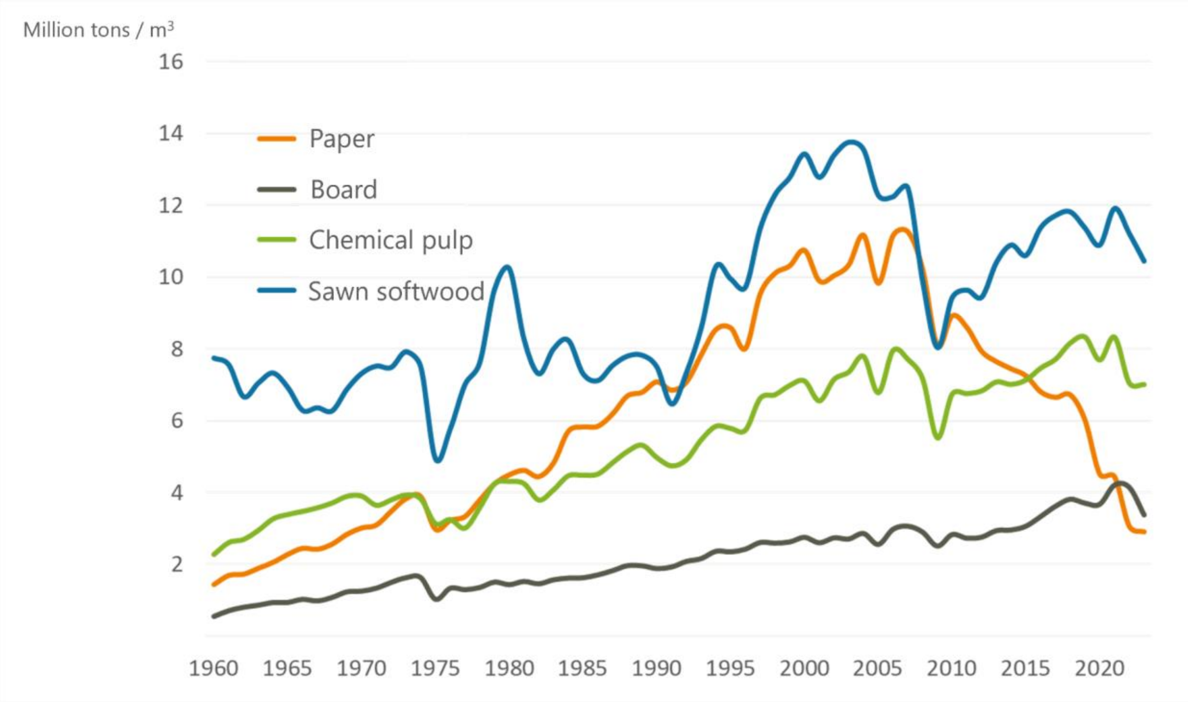


Figure 1. Forest industry production volumes in Finland (Finnish Forest Industries Federation 2024)

This report examines the potential production volumes and value added of forest-based products ranging from products that are still at development stage, to products that have already been piloted or are approaching the production phase. Products and solutions aiming for higher value added can be divided into two categories: improving current solutions and future innovations. The first category consists of new solutions in wood construction, wood-based textile products and fibre-based packaging. The future products presented in this report include the use of nanocellulose and lignin in novel materials, as well as the most promising biomedical applications. The figures and estimates presented in the report are rough estimates, especially for product groups that are still far from the production scale, which is why the calculations presented herein should be considered indicative. Nevertheless, the calculations have been extended to the sectoral and national economy levels, aiming to provide a more comprehensive estimate of the economic significance of the new products and their production.

The discussion opener by Natural Resources Institute Finland, Luke, (Lintunen et al. 2023) examined the goal set in Finland's National Bioeconomy Strategy to double the value added in the bioeconomy from the forest sector's perspective. It was limited by the availability of information about new products and therefore examined the potential of a rather limited product portfolio to achieve the goals set. In this report, the product portfolio has been expanded, in particular, by considering further processing opportunities offered by pulp and lignin. Furthermore, the forest sector's value added is not forced to be doubled as defined in the National Bioeconomy Strategy. In contrast, production levels are based on scenarios considering the availability of raw materials and future market demand.

This report is limited to technical and financial variables, and challenges related to biodiversity and climate change, for example, have not been examined. It is assumed that new products and their production will not increase the consumption of forest-based raw materials and will not correspondingly generate more adverse environmental and climate impacts than the current production. It should also be noted that forest sector products are largely compatible with the principles of the circular economy. Paper and board fibres withstand recycling much better than plastic. Paper fibres can be recycled 5–7 times and board fibres even more than 20 times before they start to lose their mechanical properties (Eckhart 2021). Bio-based precursors also enable the development of biodegradable materials for applications where it is challenging to recover materials from the environment in which they are used.

2. Steps to increase the value added in the forest sector

Economic growth in Finland's forest sector requires changes in production chains. Considering climate goals, future growth in the forest sector cannot be based solely on increasing felling volumes. Even though forests continue to be a net carbon sink in Finland, the entire Finnish land use sector changed from a carbon sink to a carbon source in 2021 (Natural Resources Institute Finland 2022). To maintain the forest sector's important role for Finland's economy in a way that is sustainable for the climate, there must be a shift from sawn timber and pulp exports towards more valuable products. This report focuses on product groups and scenarios that help increase value added in Finland's forest sector. The examined ways to increase value added in the forest sector have been divided into two categories: improved current solutions and future innovations (Figure 2). The first category consists of solutions that generate value added in building and packaging materials and wood-based textiles, as well as all the different ways in which new investments can improve energy efficiency in the forest industry. Regarding future innovations, this report focuses on the further processing of pulp into nanocellulose and textile fibres. Nanocellulose can be used in wound care, filtration membranes or even cell and tissue engineering. The more efficient use of side streams is another key step to increase value added. This report focuses especially on the application opportunities offered by lignin. While hemicellulose and bark extracts are other attractive side streams (Amorim et al. 2019, Abik et al. 2023), they are not discussed in this report. Briefly put, it can be stated that challenges with hemicellulose are associated with the raw material's production process. The separation of different grades of polymeric hemicellulose generates significant costs, restricting their attractiveness in potential applications. However, monosaccharides are regarded as useful building blocks for chemicals.

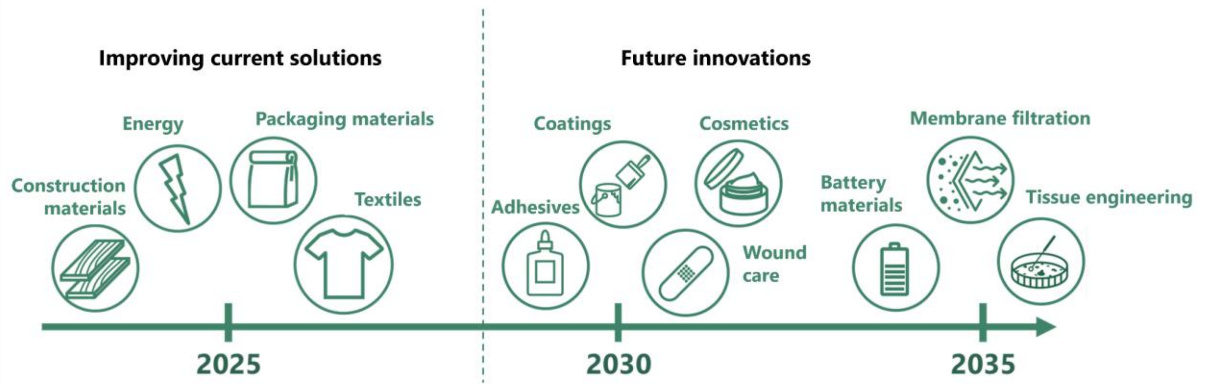


Figure 2. Examples of current bio-based solutions and future innovations.

2.1. Improving current solutions

2.1.1. Wood construction

Finland's Government Programmes have sought to promote wood construction ever since the mid-1990s. Long-lived and recyclable wood products increase carbon sequestration and help mitigate climate change. Wood construction is justified also from the perspectives of domestic employment and regional economy. Wood processing, productivity and value added can be enhanced through wood construction. Finland's forests grow 103 million cubic meters (m^3) of roundwood annually. Of our annual production volume of approximately 12 million m^3 of sawn timber, 75% is exported. In 2021, 0.89 million m^3 of wood were used in new buildings and 0.78 million m^3 in renovations in Finland (Forecon Oy 2022). It can be said that the volume of wood used in construction in Finland is very low compared to our forest resources.

Finland's amended building act (139/2022) is expected to enter into force on 1 January 2026 (Ministry of the Environment 2023), after which environmental impact assessments of buildings must cover the carbon footprint in the building permit phase. As a result, the attractiveness of wood as a domestic, local, renewable and environmentally friendly building material will increase. Through wood construction, the value added could significantly be increased without increasing felling volumes if mechanical forest industry products were processed more than at present in Finland. This requires determined measures, societal changes, multidisciplinary research, and new innovations.

Two thirds of all buildings in Finland are residential buildings. There are almost 3.2 million registered housing units in Finland, and some 35,000–45,000 new homes have been built annually during the last 20 years. This means that our building stock is being modernised at an annual rate of more than 1%. In addition, there are roughly half a million summer cottages in Finland, and 7,000 new leisure time buildings are built each year. Almost 99% of all summer cottages are made from wood. Some 7,500 new detached houses are built annually, with wood construction accounting for more than 85%. Finland is second only to Spain in Europe measured by the proportion of housing units in apartment buildings: they account for 47% of all Finnish housing units. Each year, some three quarters of all new homes are still built in apartment buildings. In Finland, wooden apartment buildings taller than two storeys have been allowed since 1995. When small apartment buildings of two storeys are also included, the market share of wooden apartment buildings is roughly 6% at present.

This report focuses on two key scenarios involving changes in the use of wood in construction, with which the value added of domestic wood could be increased significantly using currently commercially available technologies:

1) In the future, the frames of apartment buildings would be built from domestic cross-laminated timber (CLT) or alternatively from laminated veneer lumber (LVL) instead of concrete.

2) As a result of changes in Finland's fire safety regulations (Ministry of the Environment's decree 848/2017 on the fire safety of buildings), wood fibre-based thermal insulation solutions would be permitted in buildings taller than two storeys.

Both scenarios would generate significant climate benefits by replacing emission- and energy-intensive building materials (concrete, mineral wool) with the domestic wood-based products mentioned above.

Value added scenarios

1) Apartment buildings built each year in Finland would be built using domestic CLT

In Finland's wood construction, the most significant growth potential lies in apartment buildings. The use of CLT frames and prefabricated elements has increased the most in the construction of new wooden apartment buildings in Finland. Between 2018 and 2023, some 35,000 new apartments were built in Finland each year. The average floor area of a Finnish apartment is roughly 70 square metres (m^2). A wooden apartment building with a CLT frame requires 0.58 m^3 of wood per square metre on average. In apartment buildings with a composite or concrete frame, the amount of wood in the structure is significantly smaller (Figure 3).

Figure 3. Amounts of wood, concrete and gypsum board in apartment buildings. The consumption of materials has been calculated for a residential building of six storeys (roughly 1,500 m^2) with an aboveground civil defence shelter.

If all apartment buildings were built with a CLT frame in the future, they would require 1.4 million m^3 of wood (35,000 apartments × 70 m^2 per apartment × 0.58 m^3 per m^2).

The purchase price of sawn timber for the industry is approximately €300 per m^3 and the selling price of domestic CLT is roughly €1,000 per m^3. In this context, instead of exporting sawn timber, wood should be processed in Finland to produce CLT and used extensively as the frame material in new apartment buildings as a substitute for concrete. Adhesives account for roughly 1% of the weight of CLT, and their price is €1 per kg. Lignin-based adhesives could also potentially replace current polyurethane or plastic adhesives in CLT in the future. This would also have a positive impact on the value added of Finland’s forest sector, which is discussed more in Section 3.2.1.

2) Wood fibre-based thermal insulation solutions would mainly be used in buildings.

In construction, the significance of environmental perspectives is constantly increasing in the national building codes of all EU Member States. This will result in the increased use of ecological and renewable building materials and a higher energy efficiency in buildings by improving the effectiveness of thermal insulation. While wood fibre-based thermal insulation solutions could be used more extensively in construction, their use in buildings of more than two storeys is mainly prohibited by Finland’s fire safety regulations. Mineral wool (glass and rock wool) is the most commonly used thermal insulation material in buildings in Finland. Its fire rating is A2, which is the requirement for thermal insulation in buildings of more than two storeys. Wood fibre-based thermal insulation solutions can achieve fire rating B when flame retardants are used (Figure 4). Permitting the use of wood fibre-based thermal insulation solutions in buildings of more than two storeys in Finland requires changes in our fire safety regulations.

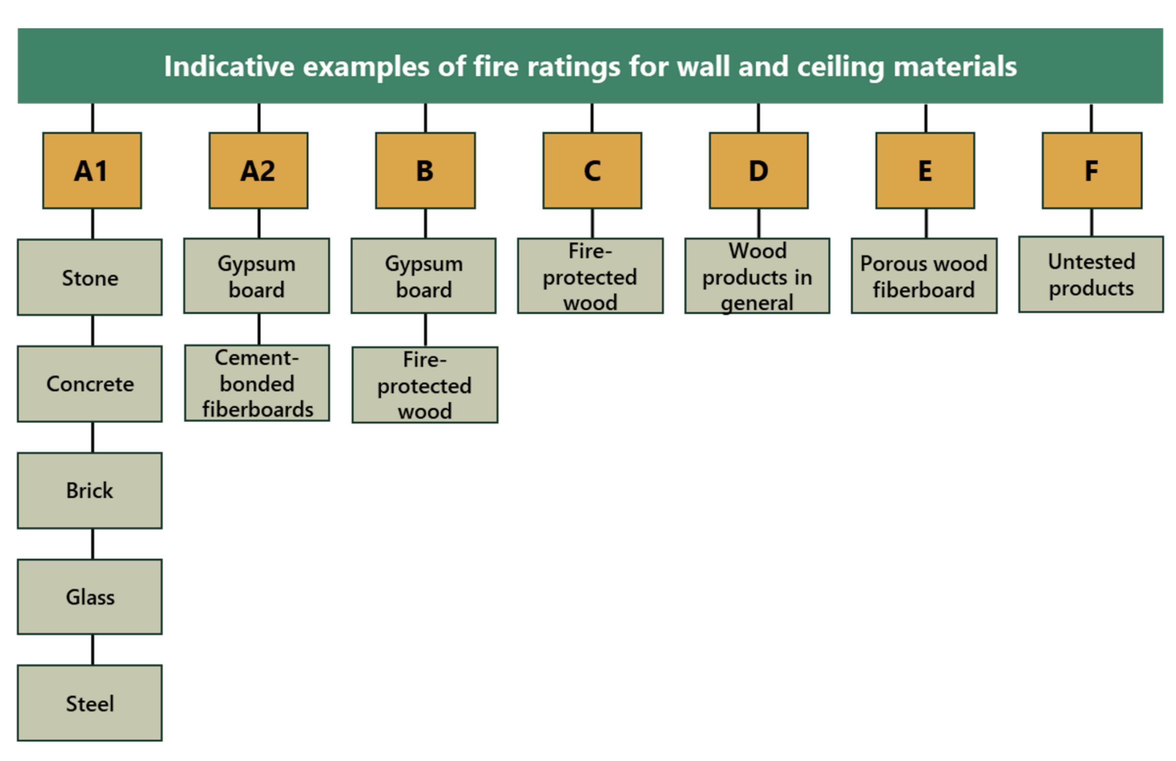


Figure 4. Indicative examples of the fire ratings of wall and roof materials.

The most commonly available wood fibre-based thermal insulation products include sprayed pulp wool or pulp wool boards made from recycled newspapers and insulation boards made from pure wood fibres. Recycled paper account for 90% of pulp wool and flame retardants (boric acid and magnesium sulphate) for the remaining 10%. In an insulation panel made from pure wood fibres, wood accounts for roughly 80%, and water and flame retardants (e.g. ammonium sulphate) for 20%.

The purchase price of energy wood fractions from the Finnish forests (twigs, branches, chips and sawdust) is roughly €20 per m^3 if they are used close to their source. In most cases, it is difficult to find buyers for energy fractions due to high transportation costs. The selling price of wood fibre-based thermal insulation products is roughly €145 per m^3. In Finland, the total volume of the thermal insulation market for buildings is approximately 5.1 million m^3 (Figure 5). By enabling domestic wood fibre-based thermal insulation solutions and shifting to their extensive use in new buildings and renovation projects, the value added generated by the use of wood procured from Finland's forests could be increased significantly.

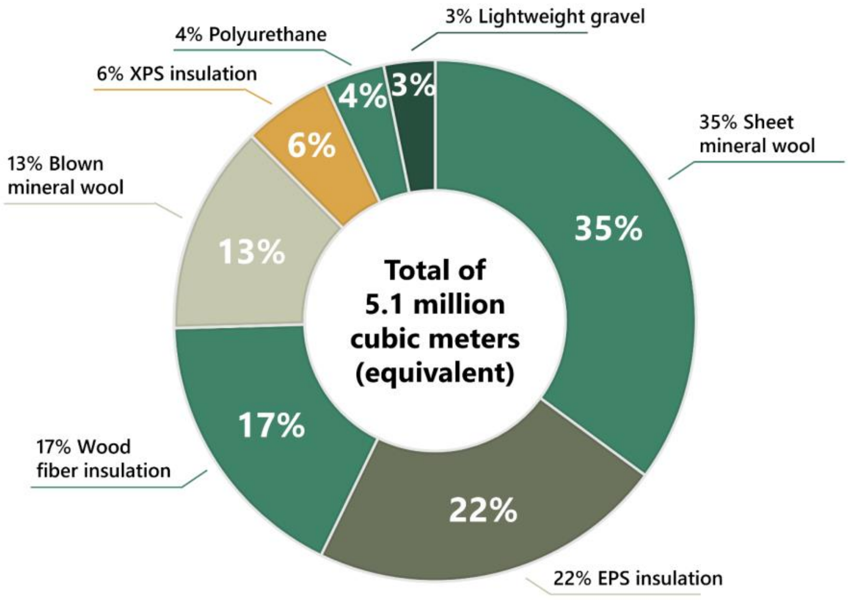


Figure 5. The use of thermal insulation products in Finland in 2022 by insulation material. The total volume of the thermal insulation market for buildings is approximately 5.1 million m^3 (Rakennustutkimus RTS Oy 2023).

The values presented in the text are based on interviews of specialists from companies that manufacture wood products: CLT Finland Oy and Hunton Oy.

2.1.2. Packaging material

Recyclable pulp- and cellulose-based packaging materials play a significant role in value chains in the circular economy and bioeconomy, especially in competition with synthetic plastic packaging. In recent years, the recycling rate of fibre packaging has ranged from 70% to 90% (Eurostat 2023 1), whereas that of plastic packaging has been roughly 40% in Europe (Eurostat 2023 2). On a global scale, as much as 90% of plastics are not recycled (Plastics Europe 2023), and plastic packaging waste has been identified as a significant source of microplastics. However, the growth potential of high-volume fibre materials and the value added they can generate are limited due to the scarce, albeit renewable, raw material resources and the low price of packaging material. Currently, synthetic plastics such as polyethylene and polypropylene have very competitive prices, and their performance in food packaging in particular is often superior. New innovative bio-based packaging solutions, including films, flexibles, and barrier material, can be expected in the near future, with their properties being competitive with conventional plastic packaging, even in the field of flexible packaging (Koppolu 2024, Khakalo et al. 2020). A potential increase in the market share of fibre-based packaging depends especially on regulations on fossil-based materials, consumers' stricter requirements, consumer awareness and environmental aspects (Technavio 2023).

A packaging barrier is a preventive or blocking material (film or coating) designed to protect the packaged product by preventing transfer of compounds such as oxygen, moisture, or grease between the product and the environment. Barrier materials are most commonly used in packaging to protect products from changes in humidity and/or oxidation (Vähä-Nissi et al. 2020

This report examines the value of the global packaging market and assesses the growth potential of fibre-based packaging material using market reviews. According to a recent packaging market review, the value of the global packaging market was €980 billion in 2022, and it was estimated to increase to €1,200 billion by 2027. Figure 6 presents the breakdown of the global packaging market by material category. Board packaging has the largest market share at 34%, and its annual growth rate is estimated at roughly 4% in 2022–2027. Board packaging could generate value added of €1.4 billion in Finland. In 2019, the value added was estimated at €0.7 billion (Lintunen et al. 2023), as a result of which we expect the application to have a significant growth potential. This can partly be explained by the increase in total board production but also by the better performance of the packaging material, enabling higher prices.

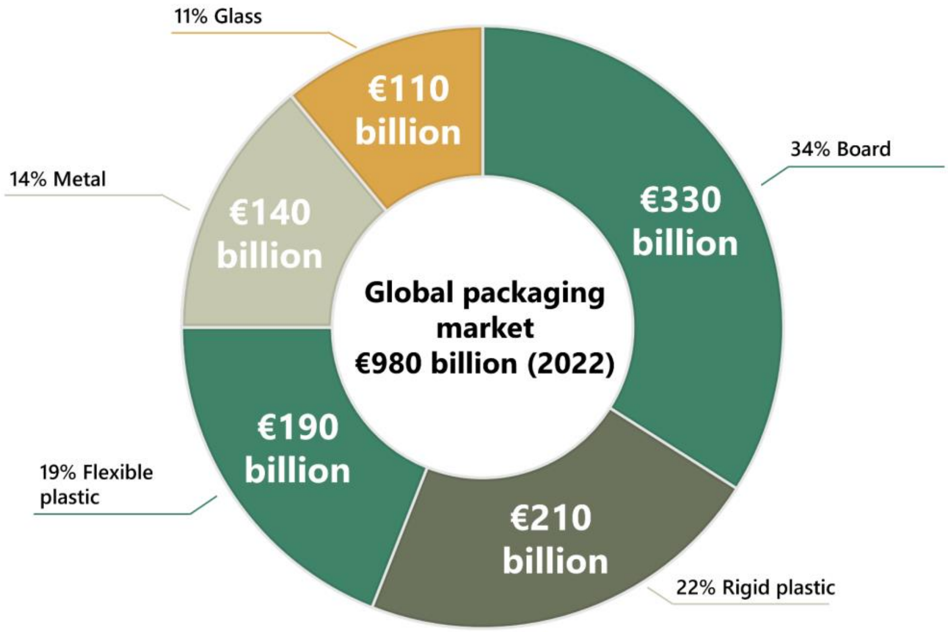


Figure 6. Breakdown of the global packaging market by material category. The annual growth rates of different packaging materials in 2022–2027 were: board 3.9%, rigid plastic 3.9%, flexible plastic 4.2%, metal 4.1%, and glass 3.5% (modified based on the Technavio 2023 market review).

In addition, this report includes an assessment of flexible cellulose-based packaging which was identified in the analysed market review but its potential share in the sector of flexible packaging material was not estimated. Another market review (Metsä Group 2023) estimated the annual growth potential of fibre-based packaging material (excluding board) at 2% in 2021–2026 offering more opportunities to increase the value added through such materials as nanocellulose-based barriers.

The market for fibre-based packaging is growing and may replace more conventional packaging especially in the food sector. As a more ecological option, fibre-based packaging solutions aim to take over the market share of plastic film packaging (flexible and rigid plastic) in line with a more general trend towards non-fossil-based packaging materials. The value of the packaging film market is estimated at roughly €140 billion in 2023 and is expected to grow by 4% per year (Future Market Insights 2022). In contrast, the value of cellulose-based flexibles are estimated at approximately €790 million in 2024, with annual growth being some 5% (Future Market Insights 2023).

Currently, fibre-based board packaging accounts for 34% of all packaging, and its market share is expected to continue its growth at a steady annual pace (Technavio 2023). More growth potential is expected in flexible packaging. Currently, cellulose packaging only accounts for 0.57% of all flexible packaging, but as a result of consumers' stricter requirements, consumer awareness and environmental aspects, significant opportunities may open up for fibre-based solutions in the flexible packaging sector as well (Future Market Insights 2022, 2023). This report estimates the value added generated by flexible cellulose-based flexible packaging and nanocellulose-based packaging barriers at €690 million (Figure 10; Packaging Plus category) with the assumption that the cellulose fibres required for the packaging material production can be obtained from pulp that would be otherwise exported as presented in the section *Further processing of exported pulp in Finland*.

2.1.3. Textile industry

The development of cellulose-based textile fibres is significant in Finland. The aim to develop new fibres comes from the shortage of cotton and the challenges related to oil-based fibres. Various fibre innovations include Spinnova, Kuura, Infinna, Norratex, Biocelsol and Ioncell. While some of these technologies are approaching the commercialisation phase, others are still under development in the laboratories of universities and research organisations. What is especially positive is that there are already several pilot plants in Finland.

Polyester and cotton account for the majority of global fibre production. In total, the global consumption of various textile fibres is roughly 113 million tons a year (2020). Of this, natural fibres have covered some 32 million tons, of which cotton alone has accounted for 26 million tons. The global production and consumption of textile fibres have almost tripled during the last 30 years. The production of natural fibres has not experienced any significant increase, as growth has nearly exclusively come from the rapid rise of synthetic fibre production (Finnish Textile and Fashion 2022).

The value addition potential of pulp-based textile fibres is based on the further processing of pulp, rather than from the additional production of pulp. To ensure a sustainable raw material base, investments must also be made into the recycling of textiles. The value addition potential depends on how far the textile value chain can be extended in Finland. At its shortest, the value chain will only cover the production and spinning of fibres, but it can be extended to the production of textiles and even to the production of clothes. It can be assumed that, if the volume of textile fibre production rises to a significant level in Finland, the majority of fibres will, however, not be further processed in Finland. The Finnish textile industry appears to be the most competitive in the market of design clothes, the volume of which accounts only for a small part of the textile industry's full volume.

Pulp processed into textile fibres is not available for other use. Consequently, the processing of textile fibres from pulp would in practice displace the domestic or foreign production of paper and board. From value-addition point of view, the most advantageous scenario for Finland would be that part of the pulp that is currently exported would be processed into textile fibres so that their production would not supersede domestic paper and pulp production.

The previously published discussion opener on doubling the forest industry's value added relied heavily on increasing the production of textile fibres (Lintunen et al. 2023). However, it should be noted that Finland's textile fibre production capacity remains limited. The expected short-term total annual capacity of bio-based textile plant investments in Finland is 100,000–150,000 tons (Finnish Textile and Fashion 2021). In this report, Finland's textile fibre production volume is expected to be 300,000 tons in 2035. If we assume that a million tons of the three to four million tons of exported pulp can be further processed in Finland, 700,000 tons of exported pulp could be used in other highly processed products, including filtration membranes, wound care and tissue technology.

2.1.4. Energy

Finland does not have any significant opportunities to increase the direct use of biomass as energy. In contrast, an improved energy efficiency in the forest industry, new processing solutions and the more effective use of side streams will lead to increases in the generation of renewable electricity and decreases in the use of external industrial fuels.

Reducing fossil fuels

Globally, the forest industry consumes a significant amount of fossil fuels by generating electricity from coal, for example. In Finland, up to 90% of forest industry fuels were renewable in 2022. In the pulp industry, the most significant fossil fuels include natural gas and oil used in lime kilns. In practice, peat and coal are no longer used. Four mills have already invested in gasifiers to run the lime kilns. When bark will be used as fuel in gasification, there will be no more need for fossil fuels. The number of lime kiln gasifiers is slowly growing through replacement investments.

Larger electricity generation

The new recovery boilers at the Äänekoski and Kemi bioproduct mills can cover roughly 250% of the pulp mill's electricity demand and are excellent examples of Finland's long-term innovation policy. These new mills use innovative process solutions to generate 1.4 megawatt-hours of electricity per air dry ton (MWh/ADt) from black liquor using the recovery boiler alone, while most current mills produce only roughly 0.5 MWh/ADt. In fact, the Kemi and Äänekoski bioproduct mills have increased the generation of renewable electricity by one percentage point in Finland. When the cost of new recovery is €300–500 million and the repayment period through energy is approximately ten years, subsidies are required to speed up the additional generation of renewable electricity.

Energy efficiency

Finland has been able to improve the total energy efficiency of the forest industry by more than 2% a year (Kähkönen et al. 2019). Government organisations such as the Sustainable Development Company Motiva have contributed to this significant achievement. Key changes include the more efficient consumption of water, the higher dry matter content in black liquor and paper machine innovations. If the Finnish forest industry can make replacement investments, this positive trend will continue in the future.

2.2. Future innovations

2.2.1. Effective use of side streams – lignin

Increasing felling volumes is not a sustainable option due to its climate and environmental impact. This is why it is important to consider more effective ways to use the forest sector's side streams. As a result, the value obtained from forests can be increased without making any compromises over climate and biodiversity goals. Lignin is one of the most interesting side streams. In Finland, some four million tons of usable lignin is generated in conjunction with pulp production. This lignin is mainly used in the generation of steam and energy. However, more lignin is often generated than what can be used in a recovery boiler. This offers opportunities to use lignin in various materials, while promoting the additional production of pulp and increasing the forest sector's profitability (Dessbesell 2020).

The amount of usable lignin in Finland (four million tons) was calculated with the assumption that the volume of pulp production is eight million tons, which is based on the average production volume of the last two years (Finnish Forest Industries Federation. Statistics).

$$Amount\ of\ lignin = \left(\frac{pulp\ production}{average\ yield}\right) * av.amount\ of\ lignin\ in\ wood = \left(\frac{8}{0,5} * 0,25\right)$$

Next, we will examine the use of lignin in various products in two different scenarios, assuming that either 20% or 40% of all lignin generated can be used in applications other than energy generation. This is equivalent to roughly 0.8 or 1.6 million tons of lignin annually. It should be noted that any changes in pulp production volumes have a direct impact on the availability of lignin. In the cautious scenario in which 20% of all lignin is used in various products, the value added generated by lignin is estimated at roughly €670 million a year (Figure 8). This calculation is based on the assumption that lignin will be used extensively in various applications. The percentage of each application from all available lignin was estimated based on the following criteria:

- The size of the global market for the application (Figure 7)
- The percentage of a product that can be replaced with lignin
- The technology's degree of completion
- The value added potential/calculated profit margin

If the examined application is already commercial or close to the commercialisation phase, its market was considered to be large, or if a large percentage can be replaced with lignin, it was assumed that a larger part of all available lignin can be used in the application. Because lignin is not yet used on a large scale, it is challenging to estimate profit margins. However, profit margins were estimated by taking into account the need to modify or purify lignin for each application relative to the price of the material being replaced. For example, when lignin is used in plywood adhesives, it is known that lignin can replace at least 40% of the phenol. As the price of phenol is €1.2–1.5 per kg, the price of lignin cannot be more than €1.5 per kg. Lignin production costs were estimated by comparing the production of lignin to similar processes and by interviewing industry specialists. The selling price was set close to the price of the material being replaced.

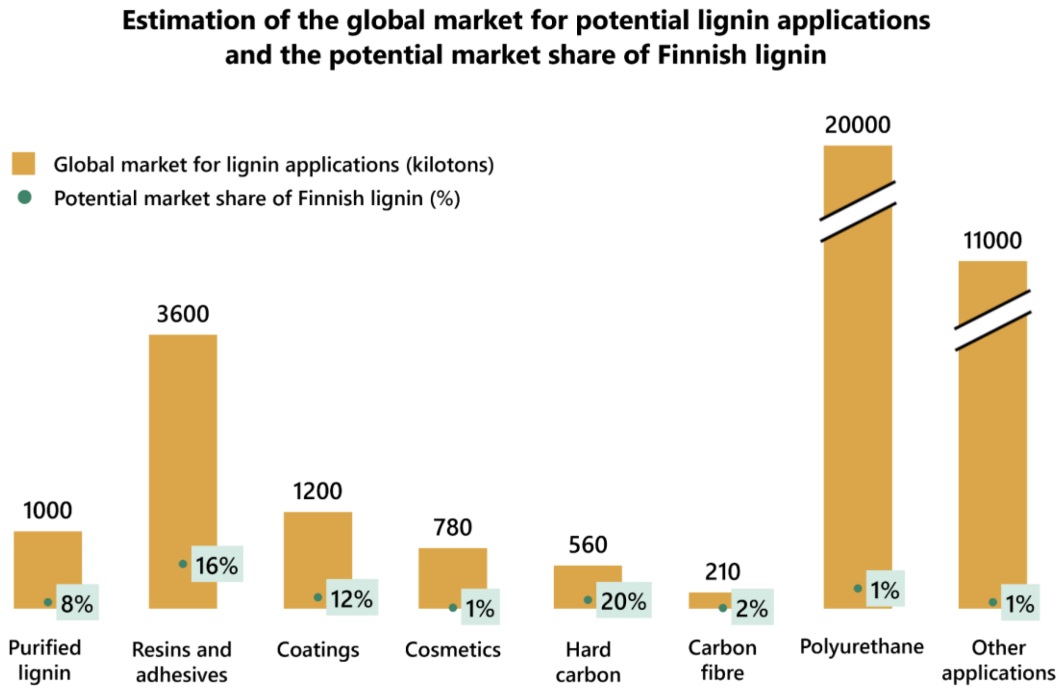


Figure 7. An estimate of the global market for potential lignin applications and the potential market share of Finnish lignin.

Based on the estimates prepared for this report, hard carbon, resins and adhesives, as well as polyurethane are applications that generate the highest value added (Figure 8). The use of lignin as an adhesive is a relatively advanced application. Several technologies have been developed in Finland to produce reactive lignin that would enable phenol to be replaced in phenol-formaldehyde resins or even fully formaldehyde-free wood adhesives with a lignin content of more than 90% (Henn et al. 2022). Hard carbon means carbon made from lignin that could replace fossil graphite in batteries. A good example of this is the Lignode® material launched by Stora Enso, which has been produced in the Sunila pulp mill's test facility since 2021. While the shutdown of the pulp mill in 2023 was a setback for Lignode production, Stora Enso's strategy to develop bio-based material innovations has remained unchanged, and the company has later announced that it will investigate competitive locations for the production of Lignode on a commercial scale. The "other applications" category includes significant applications that are already in use such as the depolymerisation of lignin and its use as a source of aromatic chemicals, and the use of lignin as a water reducing agent in concrete, as well as products that only have a minor impact on value added, either due to their small volume such as the use of lignin as a UV protection agent in sun lotions or their small value added (purified lignin).

In contrast, it can be said that the same value added of €800 million could be achieved if lignin was mainly used as a water reducing agent in concrete (Lintunen et al. 2023). In other words, if 20% of all lignin was used in material applications, the lignin application selected would not have any significant impact on the value added generated by lignin. Due to the current geopolitical situation and the growing demand for renewable energy, it is probable that, during the next five years, the majority of lignin will still be used in energy generation, while only a small part will be used in material applications, which will reduce the impact of lignin on value added in the forest bioeconomy.

The use of wind and solar power is growing steeply in Finland. For climate change mitigation, it is also important to reduce any excess burning of wood and forest residues. Measures have been taken along these lines in recent years. Emission Free Pulping, a significant joint project of the forest industry and the scientific community for emission-free pulp production, was launched at the beginning of 2024 to significantly reduce biomass burning (VTT Technical Research Centre of Finland 2024). Considering this future outlook, another scenario calculation was made, in which 1.6 million tons, or 40% of current lignin production, would be used in materials and chemicals. While this scenario is unlikely to be materialised in the near future, 40% of lignin can be recovered at a modern and energy-efficient mill (Argyropoulos et al. 2023), and this scenario could, therefore, be possible by 2035 and would generate some €1.5 billion in value added. Figure 8 presents the share of different lignin applications of the achieved value added when using 20% or 40% of lignin in products.

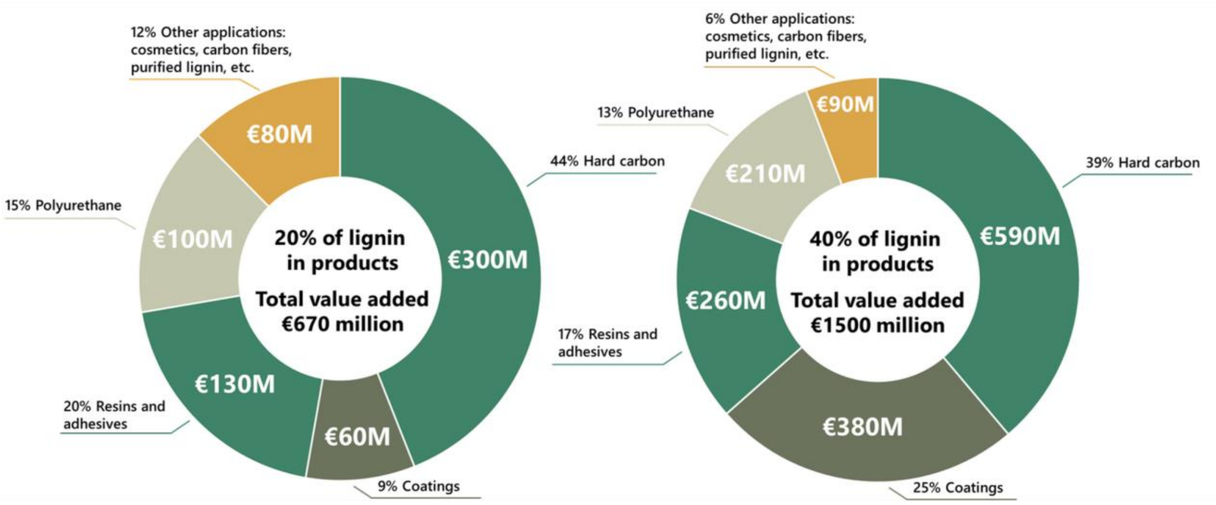


Figure 8. The share of different lignin applications of the achieved value added, assuming that 20% (800,000 tons) or 40% (1.6 million tons) of lignin is further processed into products.

Carbonised lignin such as hard carbon can replace graphite as the anode material in lithium and sodium batteries and can also be used more extensively in energy storage applications. The global battery market is expected to increase tenfold during the next five years as a result of electric vehicles and the growing need for large energy storage systems. Battery companies are planning to invest more than €6 billion in Finland (Association of Finnish Technical Traders 2023). Large amounts of lignin can be used in these applications because its colour and heterogeneity do not present any obstacles in them. The selling price of hard carbon can also be relatively high which increases the potential value added (€20 per kg). For these reasons, hard carbon was estimated to have a high potential, and 40% of all available lignin was allocated to it in this report. In contrast, it should be kept in mind that finding reliable information about production costs remains challenging, the output remains fairly low (35–45%), and the market is still developing.

Due to poor reactivity and low solubility, lignin generated in the pulp production process often needs to be modified chemically or fractioned before using it in adhesives or resins. Recently, the opportunities to use lignin have, however, been also increased in a new attractive way: by processing lignin into nanoparticles. These round particles that disperse in water are excellent emulsifiers and offer opportunities to use lignin in new applications such as sun lotions (Österberg et al. 2020). Lignin nanoparticles also provide better properties for coatings. In this report, the lignin content allocated to coatings was increased in the 40% scenario because the nanoparticle technology can be assumed to develop (Henn et al. 2021). The ability of lignin to offer protection against harmful UV radiation and oxidation generates added value for coatings and cosmetic products. However, it should be noted that the amount of lignin used in these applications is limited by its brown colour. According to a techno economic analysis, the nanoparticle production process is scalable, and a startup company called LignoSphere is seeking to commercialise the technology.

Similarly to wood construction, it is important to increase the processing value of lignin in Finland. Figure 9 presents examples of lignin value chains from black liquor to lignin-containing coatings, adhesives and battery materials.

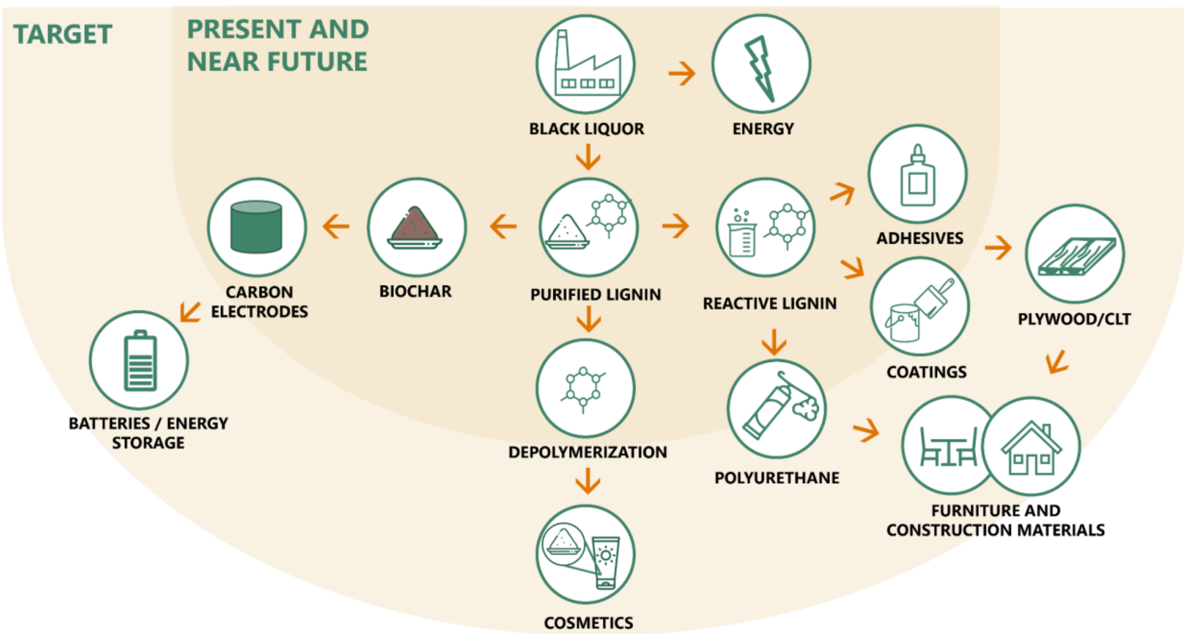


Figure 9. Examples of value chains in lignin processing.

Finland is already home to several further processing companies, including Prefere, Kiilto, Teknos and Tikkurila, that enable extending value chains in Finland. The use of Finnish lignin in place of imported phenol or fossil graphite represents sustainable development both financially and ecologically.

2.2.2. Further processing of exported pulp in Finland

The further processing of export market pulp in Finland could open up opportunities for a higher value added without increasing felling volumes. This report examines cellulose-based material solutions in which part of pulp fibres to be exported (1 million tons), equivalent to some 25% of the total volume of exported pulp, would be used as raw materials. We selected products and applications in which cellulose in its different forms has shown to have specific capabilities and the ability to replace fossil raw materials. The product categories and their potential value added are presented in Figure 10.

Of the material categories presented in Figure 10, Pulp Plus consists of nanocellulose production (micro- and nanofibrillated cellulose) and dissolved cellulose used in textile manufacturing. This category would generate €1.5 billion in value added. Packaging Plus includes flexible packaging and barriers, in which nanocellulose in particular plays an important role in terms of performance (low oxygen penetration) and the replacement of plastics. A more detailed examination of packaging is presented in the *Packaging material* section. The textile fibre category consists of more processed cellulose material, which can be used in yarn production. This means that its value added per produced ton is higher than that of the materials in the Pulp Plus category.

Filtration membranes, wound care and biomedical applications are largely based on the use of nanocellulose as an active material component and represent products with a high value but a low volume. The examples above were selected as value added products based on recent and promising research results (Heise et al. 2021, Leppänen et al. 2022, Solin et al. 2023), a market review (Future Markets 2023) and the fact that the applications are already on a commercialisation path. In general, the use of nanocellulose, especially nanocrystalline cellulose (NCC/CNC) and micro-/nanofibrillated cellulose (MFC/NFC/CNF), is expected to increase, as it represents renewable, biodegradable as well as strong and lightweight materials which makes it an attractive raw material for products in line with sustainable development. Mechanical, chemical and enzymatic pre-treatment helps produce customised materials with exceptional physical and chemical properties (high active area, biocompatibility, film-forming and water-absorbing abilities, low oxygen penetration, antimicrobial properties and even the ability to maintain the vitality of living cells) as a result of the nanoscale structure combined with the specific chemistry of the surface (Kontturi et al. 2018, Aguilar-Sanchez et al. 2021, Rissanen et al. 2021). Currently, these properties have not yet been fully used in bio-based material solutions which could enable the generation of value added in the forest sector.

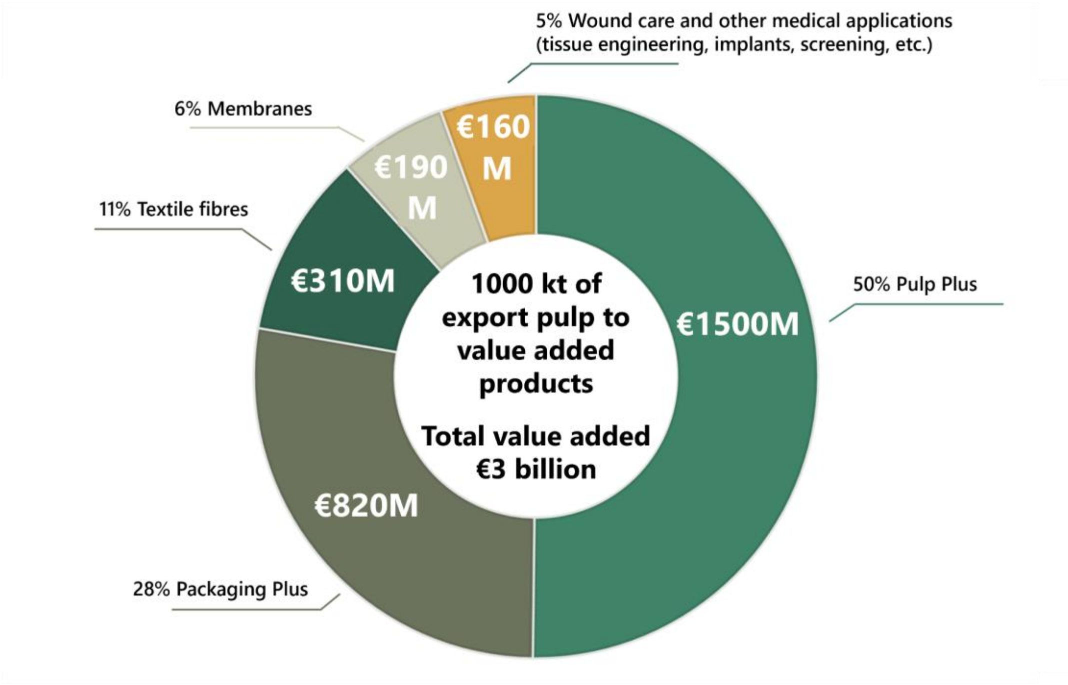


Figure 10. The potential total value added if pulp fibres were further processed in Finland.

This theme has been studied actively, and products have already been launched, especially in Japan. For example, Japanese Asics has used CNF in its running shoes, and large paper mills such as Nippon

Paper and Oji Holdings have established significant facilities to produce nanocellulose fibres. The forest and chemical industries in Europe, Canada and the United States are also engaged in this development. Based on the market review, the current production volumes of micro- and nanofibrillated cellulose are low, and most producers are selling nanocellulose fibres at roughly €50–100 per kg (Future Markets 2023). Many producers have said that prices should fall under €10 per kg for nanocellulose materials to be competitive in high-volume applications. Producers seek to develop production methods with lower costs or materials for higher value applications. It should be noted that the price per kg of sterile nanocellulose with a high degree of further processing and suitable for cell culture is several thousands of times higher than the prices mentioned above (GrowDex ®). The film-forming ability of nanocellulose is a key property especially in membrane filtration, the field of flexible packaging and barriers, as well as wound care solutions. As scalable technologies on an industrial scale are available for the production of nanocellulose membranes (Koppolu 2024, Khakalo et al. 2020), the production costs of these intermediate membrane products are no longer significant extra cost items in our value added calculations.

Membrane filters

Membrane filters are used in water and solvent purification, i.e. the recovery and separation of nano- and micro-sized particles and molecules in liquid environments. The value of the global membrane filtration market is estimated to reach €2.1 billion in 2026, and the market is expected to grow at an annual rate of 6.8% between 2021 and 2026. Key factors for market growth include the increasing use of membrane filtration technologies in wastewater treatment, and the growing demand for effective purification methods in food and beverage production, as well as the production of dietary supplements and pharmaceuticals. In addition, the growing purchasing power of the middle class and the need for high-quality products will increase the demand for water filters and reverse osmosis solutions in households. However, the most significant factor for effective water filtration technologies is that roughly half a billion people are suffering from the lack of clean drinking water.

While synthetic materials dominate the membrane market, this industrial sector is also looking for alternatives to replace fossil materials similarly to producers of flexible packaging material. In 2020, cellulose-acetate membranes accounted for 36% of the membrane filtration market (IndustryARC 2024). Cellulose-based products are suitable for water and alcohol solutions, and they are used in biological and clinical analyses, sterility tests, radiation measurements and many other applications. Based on the market review (Future Markets 2023) and a study promoted in Finland as well (Pöhler et al. 2022), nanocellulose membranes have a significant proven potential to replace synthetic membrane materials and cellulose-acetate membranes in the filtration of impurities, pollution, chemicals and biological substances. Nanocellulose membranes have even been used to separate nano-sized plastic particles from water (Leppänen et al. 2022). Based on our calculations, nanocellulose membranes that represent intermediate products in membrane filtration technologies (active material in filter units) can generate value added of €190 million. A particular challenge is that there are not many actors in Finland that promote these technologies that are under development.

Biomedical applications of nanocellulose

The attractiveness of sterile high-quality nanocellulose hydrogels and membranes is constantly increasing in modern medicine (Jorfi & Foster 2015, Orelma 2018). Biocompatible and biodegradable cellulose material is also effective in many demanding biomaterial applications, i.e. materials that replace, produce or treat living tissues. Finland is home to active R&D activities, and our strong internationally competitive knowledge base and existing infrastructure support innovations in the sector. Finnish innovations include the UPM Biomedicals wound dressing based on CNF hydrogels as well as hydrogels suitable for cell culture. The biocompatibility and biodegradability of nanocellulose have opened up opportunities for its use as processing aids and carriers in pharmaceuticals (Paukkonen et al. 2017), wound dressings, culture media suitable for cell and tissue technologies, as well as media/materials for grown tissue implants. High-quality nanofibrillated cellulose is a further processed product made from pulp fibres which offers a very high value added, albeit its volumes will be very small even if production was upscaled significantly and its use increased. This has been taken into account in our value added calculations. The total global demand for nanocellulose in biomedical products was only 15 tons in 2023 based on the estimate obtained from the commercial market review (Future Markets 2023). Based on the review, production is expected to become 20 times higher by 2035. As a result, earnings are expected to increase from the current estimate of less than €0.7 million to roughly €9 million. Currently, approximately 20 companies are developing nanocellulose for biomedical and healthcare applications, of which UPM is active in Finland and significant on an international scale.

Its mechanical durability, softness and the high water-absorbing ability make nanocellulose an ideal material for **wound dressings** to advance the formation of new skin tissue, protect wounds from secondary infections and reduce the pain experienced by patients (Koivuniemi et al. 2019, 2021, Hakkarainen et al. 2016, Kiiskinen et al. 2019). Illnesses related to aging and obesity, as well as difficult infections, make chronic wounds a globally significant clinical challenge and therefore wound care a growing market. Growing demand can be expected for NFC-based wound dressings. UPM is currently a key player in Finland, and its commercial FibDex wound dressing is especially ideal for the treatment of large wounds, skin transplants and difficult burns.

As life-sustaining materials, the most recent innovations of NFC hydrogels are related to the **cell and tissue technologies**. Supporting cell adhesion and activity, they can be used in cell culture as structures for tissues and implants (Chang et al. 2020, Lou et al. 2014, Harjumäki et al. 2019, Heuer et al. 2020). The development of these applications and related technologies are still in the R&D phase. For example, UPM's commercial GrowDex gel is mainly intended for research and also the mass screening of pharmaceuticals in the industry. Advantages of nanocellulose-based cell culture include its sterility and even quality, as well as its ability to imitate the human body's environment. The culture environment is suitable for more accurate screening in which the patient's own cells can be used (enabling personalised care). Opportunities and active research objects in the near future include bioprinted tissues and implants. Hydrogels have also been found to be ideal for the storage and transport of biological pharmaceuticals, cells and tissues (Auvinen et al. 2019, Koivunotko et al. 2021, Merivaara et al. 2021). We expect the significance of these applications to increase in medicine similarly to pharmaceuticals based on nucleic acids and proteins such as coronavirus vaccines, antibodies and cell therapy (Egli & Manoharan 2023, Dumontet et al. 2023, Martins et al. 2022, https://inflames.utu.fi/, https://www.genecellnano.fi/).

Value added calculation for the further domestic processing of pulp currently exported

The calculation was based on the production of nanocellulose, microcellulose and dissolved special cellulose for products in the Pulp Plus category. In the calculation, products were divided into two product groups, corresponding to special pulp solutions of different cost levels. Lower cost solutions were defined to be used in the production of flexible packaging, textile fibres and advanced board packaging. Correspondingly, higher cost solutions were allocated to the nanocellulose products described above. The production process and costs of special pulp with lower costs were estimated based on the production structure of cellulose-based micro- and nanofibrillated solutions described in the article of de Assis et al. (2018). Correspondingly, special pulp with higher costs was described using the estimates made by Penloglou et al. (2023). Based on these production costs, the prices of the pulp products were set at €2 per ton and €7 per ton.

These prices are fairly low. They represent the future pictured in the market review (Future Markets 2023), in which technical development has allowed production costs to have been lowered to a level at which products processed from special pulp are competitive with alternatives not based on pulp. It should be noted that, in the calculation, all special pulp solutions were processed into other products, and the price level of pulp does not have an impact on total value added in value chains because sales gains from pulp are used as inputs in the next phase and excluded from the value added calculation.

The largest cost item associated with the products processed from pulp included in the examination consists of the special pulp used in production. Because no technical or financial analysis of the production of nanocellulose membranes was available, the production costs of paper production were used to determine those of membrane production. Even if the production costs of membrane production were higher in practice, they would still be low relative to the price of nanocellulose raw materials. Because pulp prices were estimated at a moderate level, the levels of demand for further processed products were correspondingly estimated to be fairly high relative to the demand projections defined in the market review. However, the relative production volumes of processed products were set to correspond to the market review's estimates of relative demand volumes.

Profit margins were also estimated for nanocellulose products based on estimates of production volumes – by connecting a lower margin to higher volumes – and the special properties required for products such as cleanliness. It should also be kept in mind that the examined products are pulp-based intermediate products, from which end products can be processed. Insofar as these end products are manufactured in Finland, the value added in nanocellulose-based value chains can be significantly higher than what is estimated in this report. Figure 11 presents a summary of potential solutions that generate value added through the further processing of pulp fibres.

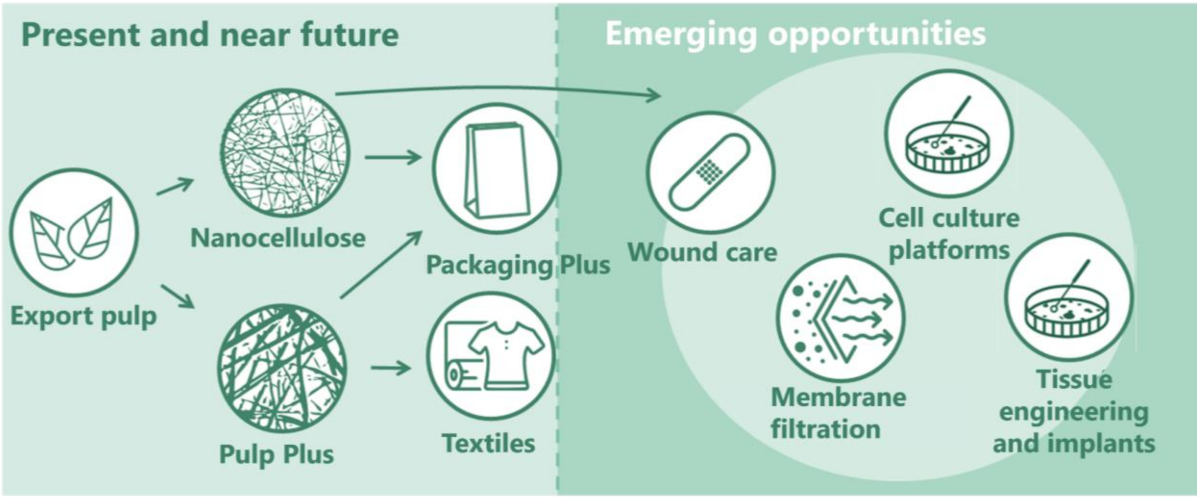


Figure 11. Potential solutions that generate value added through the further processing of pulp fibres.

2.2.3. Energy products – CCS and P2X

The green transition enables value added to be generated from the forest industry. It can be obtained from the use of bio-based carbon dioxide, one of the current side streams. The European Commission has proposed that a significant amount of carbon, approximately 450 MtCO2e, per year be recovered, transported and pumped underground. If this carbon dioxide was bio-based, it would be a technical carbon sink. Finland's official goal is to achieve carbon neutrality by 2035. As the land use sector is facing challenges with carbon sinks, technical carbon sinks could help Finland achieve this goal.

Technical carbon sinks – BECCS

When biomass grows, it sequesters carbon dioxide from the air. For example, if the carbon dioxide released through the burning of wood biomass was recovered, liquefied and transported to the North Sea by sea where it was pumped to permanent storage under the seabed, it would become a technical carbon sink, which could support Finland's carbon neutrality goal. At current prices, recovery will cost €30–60 per tCO_2, and the price of transport and storage will be €10–20 per tCO_2 at the lowest level. An advantage is that Finland is already generating some 28 $MtCO_2$ of bio-based carbon dioxide a year which means that any large-scale recovery would not require the use of wood biomass to be increased. In principle, if an EU-based market can be established, Finland would be able to help the other EU Member States, for suitable compensation, with its bio-based and existing source of only 10 $MtCO_2$. Recovery of 10 million tCO_2 per year from flue gases requires investments of €4 billion (Karjunen et al. 2022).

Electrical products – P2X

The first P2X plants are already under construction in Finland. One of the key processes in P2X technologies is the electrolysis of water, in which water is split into hydrogen and oxygen using electricity. Hydrogen and the recovered bio-based carbon dioxide can, when using a suitable catalyst, be converted into methane, methanol or transport fuels. The highest replacement value can be achieved when electro-methane is processed into transport fuels. The future potential of this business is significantly affected by the EU's possible ban on vehicles with internal combustion engines. If 10 million tCO_2 per year was converted into e-products (e-fuels and e-chemicals), investments of €15 billion would be required, plus investments of €30 billion in the generation of additional green electricity such as solar and wind power. Investments in the generation of additional electricity will be made in Finland without the government's significant input.

The production of methanol has been investigated in several projects. Fossil-free e-methanol is expected to become a significant ship fuel. Methanol can already be processed into chemical industry products such as adhesives. Renewable methanol already has an existing market, and it has a significantly higher price than fossil methanol. If 10 million tCO_2 per year was converted into methanol, 9,000 MW of electricity would be required to produce 7.5 million tMeOH. The revenue of this product would be €7–8 billion. Energy products will be discussed in more detail in upcoming reports.

2.3. Total value added in the forest sector

By summing the estimated value added of the forest sector's product portfolios presented above, the total value added for 2035 will be roughly €15.4 billion (Figure 12). This means that, in the scenario, the total value added will increase by more than 80% compared to 2019. While this is a significant increase, it falls short of the previous scenario project's estimate by roughly 20% (Lintunen et al. 2023). The current report examined a scenario in which felling volumes were kept at the current level and it was assumed that one million tons of exported pulp could be further processed in Finland, 40% of lignin could be processed into materials instead of burning, and domestic CLT and wood-based insulation solutions could be used in apartment buildings. To be materialised, this scenario also requires significant steps forward in the textile and packaging sectors.

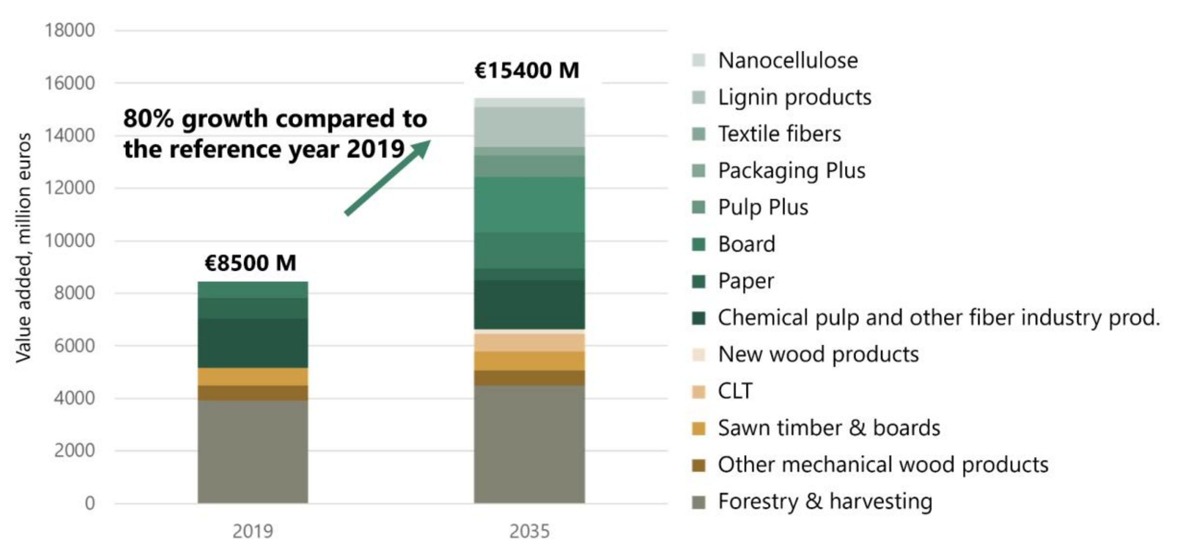


Figure 12. The forest sector's value added in the initial situation (2019) and an estimated potential (2035).

When assessing the potential financial impact of new innovations, it is important to consider each product's relative value added and potential production volume, which depends on the size of the market and the estimated future production capacity. The relationship between the value added and potential production volume is illustrated in Figure 13. Biomedical applications can be regarded as an extreme example, for which the average value added was estimated at €1,000 per kg, while production volumes were expected to remain below a ton. Sawn timber and boards are at the other extreme of the diagram. Their production volumes are more than 100,000 higher than the volume of biomedical products, but their value added per each unit produced is considerably lower. However, their large production volumes provide board and Packaging Plus, which includes packaging barriers and flexible packaging, with a significant value added. With regard to lignin, the value added per production unit increases when purified lignin is further processed into coatings or hard carbon, whose potential production volumes are also significant.

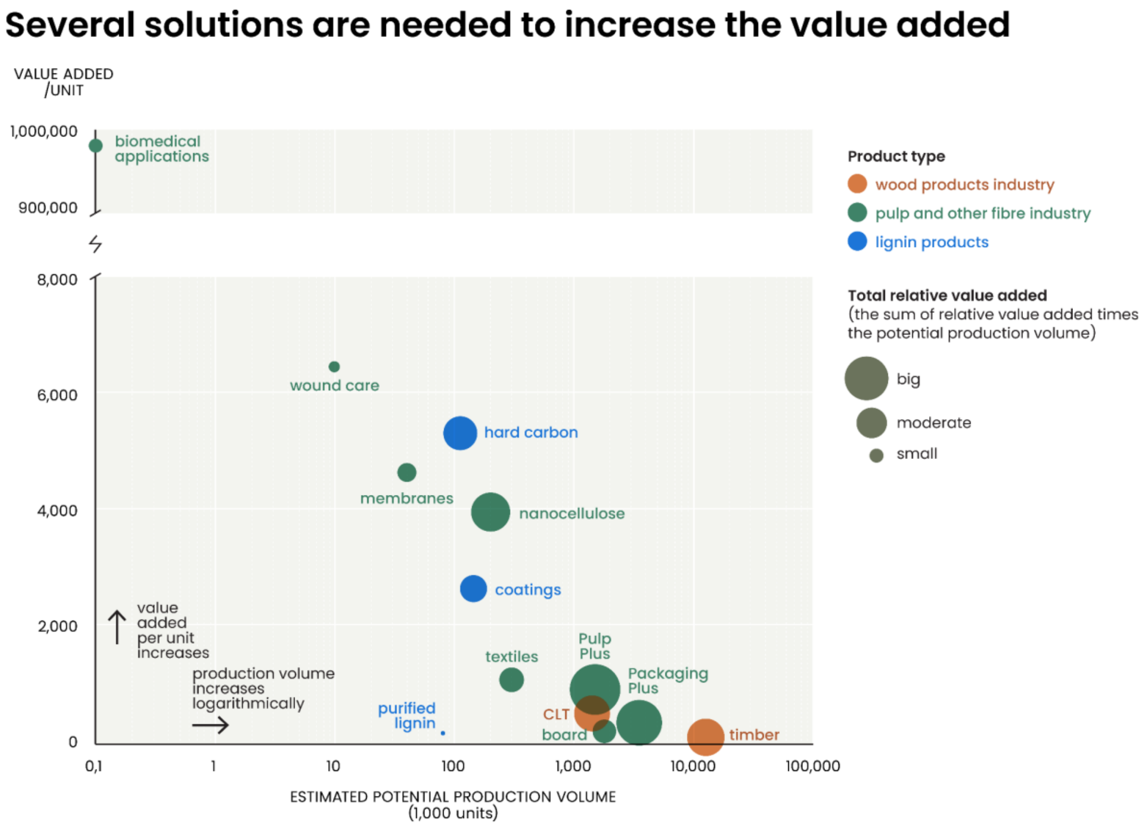


Figure 13. Examples of the estimated location of the examined products on the axes of value added and production volume. It should be noted that the axis representing production volumes is logarithmic. The sizes of the circles represent the products' estimated value added relative to one another.

According to the scenario, the forest sector's value added can be increased in Finland using materials with a higher processing value. To be materialised, this trend requires the commercialisation of new material innovations in Finland. The key question is how the development and success of innovations can be supported. Significant factors include:

1) **Fostering basic and applied research.** Radical innovations are typically based on long-term fundamental research, the results of which are advanced through applied research. There is significant high-level expertise in both wood processing and new wood-based products, and from the point of view of scientific publications, Finland is among the most active countries following China, the United States and India in the research of new innovative wood-based materials such as nanocellulose and nanolignin. The flagship programme financed by the Research Council of Finland has enabled long-term and multidisciplinary research to promote the forest sector through the FinnCERES and UNITE flagships (https://www.finnceres.fi/ and https://uniteflagship.fi/). Their activities have laid a solid foundation for new innovations, and it is important that research related to the forest bioeconomy also continues after the current flagship period. To support bio-based material innovations, funding is needed for applied multidisciplinary development to ensure, among other things, the techno economic feasibility, sustainability and performance of new materials in different applications. The doctoral education pilots funded by the Ministry of Education and Culture that started in 2024 are other significant recent RDI investments, under which universities will receive appropriations of €255 million for the training of a thousand new doctors to increase Finland's competitiveness and create opportunities for innovations (Ministry of Education and Culture 2024). Of these pilot projects, the CIMANET network will focus on the circular bioeconomy, providing training for 67 new specialists

to support the renewal of the forest sector and bio-based industry (https://www.aalto.fi/en/doctoral-education-pilot/cimanet-doctoral-education-pilot).

2) **Innovation funding.** In addition to research and specialists, material innovations typically require significant investments in production scaling during the first steps of business activities. Especially positive is the fact that the Finnish private sector is already investing boldly in startups and innovations in the forest sector and bioeconomy. In contrast, the inflexible practices of universities and the public sector can cause challenges for potential startup teams. The gap between research and commercialisation is typically wide when it comes to innovations in the forest sector, and new forms of funding are still required to cross it. To advance innovations to the production phase, a positive investment atmosphere needs to be built and maintained. The scale of investments that generate more value added can be significantly smaller than the first processing phase. Furthermore, integrating them into the existing industrial infrastructure is often necessary for the management of logistics, energy generation, and waste and side streams. Finland requires investment capital and a critical analysis of what parts of the value chain located close to the consumer market can be made competitive here.

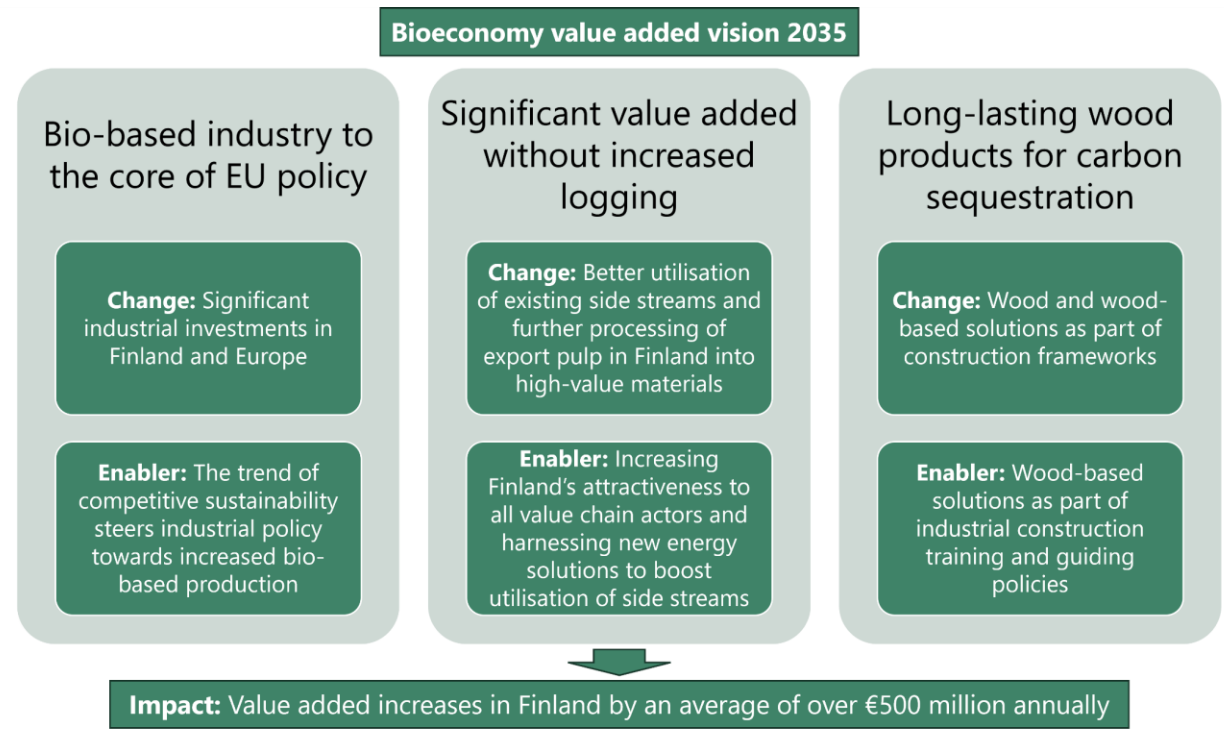
3) **Finland needs to become a more attractive environment for entrepreneurs and international talent.** Finland requires active efforts to attract international specialists here. It is important that our university-educated masters, engineers, and doctorates integrate into Finnish society. The CIMANET pilot project for doctoral programmes seeks to actively help international specialists find employment in Finland, especially in companies and research organisations. The PhD and postdoc programme launched by VTT in 2023 and Luke's doctoral programme started in 2024 support education provided for specialists and the employment of recently graduated doctors.

The significant increase in the production capacity of renewable and low-emission electricity is a major recent change in our operating environment. It will change the business logic of production in the forest sector and may enable the manufacturing of energy-intensive products and also the more sparing use of wood raw materials, as energy does not need to be generated as extensively from wood biomass. It should also be noted that, in addition to new material innovations, the recovery of carbon dioxide and new energy products offers a significant potential to generate more value added in the forest sector in a way that is sustainable for the climate. This also calls for significant investments and support through political regulations.

3. Conclusions and vision

The forest sector's value added cannot be increased significantly without major structural changes. For example, extended value chains in Finland, investments, focus on research, providing support for entrepreneurship, the availability of skilled employees and green energy are key factors to increase the value added in Finland. In conclusion, increasing the refining degree of lignin, pulp fibres and mechanical wood-based products into higher value products and using side streams more effectively in Finland would generate a significant value added without needing to increase felling volumes. Doubling the value added by 2035 in line with Finland's National Bioeconomy Strategy as defined in the previous scenario project (Lintunen et al. 2023) will nevertheless be extremely challenging.

Forests should not be treated as carbon sinks or material banks alone. When promoting climate, remediation and bioeconomy activities, it is important to assess their cost-effectiveness and environmental impact critically and comprehensively, also considering their combined impact. It is essential to understand that we need materials now and in the future. Currently, we are overly dependent on the linear use of fossil raw materials which presents challenges to us through accumulation of microplastics and climate change, the impact of which we do not even know yet. Wood-based materials offer a more sustainable option for these materials, and their production often has a smaller carbon footprint than the products they replace. However, global forest resources are insufficient to replace all fossil materials, and wood-based materials with appropriate properties have not yet been developed for all applications. Furthermore, the forest industry's need to increase the production of materials is easily in conflict with the goal to maintain biodiversity. As a result of sustainable silviculture, the forest sector can, however, have a positive impact on climate and the environment.



The bio-based industry at the core of EU policy. The EU has fallen behind the United States and China in economic development. The bio-based industry may increase the value added generated in the EU. This calls for significant measures to achieve and maintain production investments in the EU and an analysis of how further processing can be made profitable and competitive. Even though the processing of products with a high value added is not dependent on the long-term availability of raw materials to the same extent as pulp and timber, uncertainties about the opportunities to use forests in the EU cripples the investment mindset. The EU's regulation on forests has become significantly stricter and this is a key factor increasing uncertainties: there are more than 70 regulations changing over time that concerns t forests, causing uncertainties among forest owners and increasing the wood-consuming industries' wood procurement costs (Väätäinen et al. 2023)

Significant value added from new innovations without increasing felling volumes. Export market pulp should be further processed into textile fibres and micro- and nanofibrillated cellulose that could be used as raw materials in filters, packaging barriers and biomedical applications. These applications offer a high potential for value added, provided that further processing remains in Finland, extending the domestic value chain. A key question is how Finland can be made more attractive for investments, entrepreneurs and international specialists. Side streams should also be used effectively. This report focused on lignin, which should be recovered in larger volumes and further processed into materials and products. Hard carbon for energy storage, coatings, resins and adhesives in particular are significant applications that generate value added. However, this change requires investments in the Finnish value chain and new solutions to replace the current energy generated by burning lignin.

Climate change mitigation through long-life wood products. Instead of exporting sawn timber, wood should be processed into CLT or LVL in Finland and used in apartment building frames instead of concrete. In addition, any excess energy wood should be processed into wood fibre-based thermal insulation products and used in construction as substitutes for mineral wool. Recyclable wood-based products have a long life, increase carbon sequestration and help mitigate climate change. It is important that wood-based solutions are integrated more closely into construction policy in the future.

It should also be noted that forest sector products are largely compatible with the principles of the circular economy. With the current raw material resources, it will be ever more challenging to cover people's annually growing material needs without massively increasing the production of fossil materials. It is easy to predict that the significance of the circular economy will increase globally. Energy products in line with the circular economy and the recovery of bio-based carbon dioxide also offer a significant potential to generate more value added in the forest sector in the future in a way that is sustainable for the climate.

Not all raw materials and product groups within the scope of the forest bioeconomy have been discussed in this report. For example, bark extracts and hemicellulose are significant side streams that offer attractive opportunities in medicine and the food industry or as precursors for chemicals. The FinnCERES flagship programme has studied the effectiveness of lignocellulose in completely new applications. Examples include cellulose-based optical materials, sensors and diagnostics (www.finnceres.fi). Research of new applications is obviously required to advance promising research results towards the innovation and commercialisation path. When analysing the report's results, it is important to note that making reliable estimates of products in the innovation phase is challenging.

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Appendix. The calculation process

Value added is a national economy concept, and Statistics Finland (2024) defines it as follows: Value added (gross) refers to the value generated by any unit engaged in a production activity. In this report, "unit" should be understood as a production facility that is engaged in the manufacturing of a product. Value added was calculated, in accordance with its definition, by deducting intermediates (goods and services) from the unit's output. In other words, it was important for the calculation to define the output, i.e. the product price multiplied by the production volume, and the costs of intermediates. Because new products and the future market situation were especially examined, product prices, production volumes or the use of intermediates could not be evaluated based on statistics, and they were defined on the basis of estimates of future markets and production technologies. Therefore, the calculations were made using estimates based on literature and expert evaluations. In other words, the reported figures should be understood as rough indicative estimates.

The calculations were made as a result of Luke's discussion opener (Lintunen et al. 2023), which examined the goal of doubling the value added as set out in the National Bioeconomy Strategy. This report largely used the same assumptions, while the examination was expanded using a group of new products larger than the forest industry's product range. The key assumption was that the forest industry's wood consumption will remain at the 2019 level. Therefore, the increase in value added is not based on an increase in the consumption of wood. Wood consumption will also be divided between the pulp and mechanical forest industries as in 2019. In addition, new products such as pulp, paper, sawn goods and hemicellulose, as well as the manufacturing of other products of industrial branches not included in the modelling and therefore the value added will remain at the same level as defined in the discussion opener. Furthermore, the value added of the forest industry and harvesting sector was assumed to develop similarly (€4.5 billion). The examination of the value added of energy products was not included in this report.

New features in this report include product groups based on advanced special pulp qualities, various products processed from lignin, the establishment of advanced board products in the special pulp component, the updated examination of CLT, and the inclusion of wood fibre insulation products. The use of a broader product range enabled defining a more moderate value for the further processing of exported pulp in Finland (1 million tons vs. more than 3 million tons) and the smaller role of textile fibres in increasing the value added.

Production values were estimated using a restriction based on the raw material potential and assessments of the market size based on expert evaluations and literature. Product price levels were also estimated at the same time as production values. For micro- and nanofibrillated pulp, for example, it was assumed that technological development will enable relatively moderate market levels, which is why it was more reasonable to assume that product markets will be relatively large. Because not many estimates of future prices were available, product prices were estimated on the basis of production costs and profit margin rates. Production costs are determined based on the production technology used and input prices. Because special pulp products are intermediates for the next products in the value chain, their price level does not have an impact on the sector's total value added because the output related to them is offset as the next level's costs. Therefore, the total value added examined depends especially on the estimated prices of the final products in the value chain.

Information about production technologies was required to determine the price estimates described above and also to estimate the costs of intermediates. Sufficiently detailed descriptions of technologies were only available for some products, while the production costs of other products had to be estimated based on literature. To determine the costs of intermediates from production expenses, it was necessary to separate the cost of capital from production expenses and estimate their percentage. If detailed information about labour costs was unavailable, they were estimated based on the proportion of labour costs in similar production sectors as defined in sector-specific statistics in the annual national accounts.

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