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Carbon substitution and storage benefits from harvested wood products in the Norwegian forest sector

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MSC Forest Science

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Abstract

The objective of this thesis was to study the carbon substitution and storage benefits from harvested wood products (HWPs) produced by the Norwegian forest industry today and potentially in the future. Five different product portfolios, scenarios, were considered.

Information about the carbon substitution factors and end-uses of the HWPs were acquired from various sources. Monte Carlo analysis were conducted for calculation of the substitution benefits for both production and use, and the end-of-life stages. To calculate the storage benefits, methods applied by the Intergovernmental Panel on Climate Change regulations and production data were used.

Scenarios 1 and 2 were defined based on forest sector production statistics. For scenario 1 the average HWP production for the five years 2017 to 2021 was used, while for scenario 2 the 2021 production was used. In scenario 3, recently established or confirmed production capacity investments in Norway were added to the production of HWPs in 2021. For scenario 4, also non-confirmed capacity investment plans aired by the potential investors were added. In scenario 5, the exported wood in scenario 3 was used for domestic production of HWPs with increased carbon substitution factors and longer life spans.

Scenario 5 had the greatest substitution and storage benefits of all scenarios. However, the recently established or confirmed production capacity in scenario 3 also increased the carbon substitution benefit substantially compared to previous production capacity defined in scenarios 1 and 2. The carbon sink decreased for all scenarios over time. Paper products and textiles experience the fastest decline due to their rapid oxidation time. The results also revealed that the production and use stage contributed more to the carbon substitution benefit than the end-of-life stage in all scenarios. This was especially apparent in scenario 4 which had the largest share of biofuels and pellets, with no substitution benefit in the end-of-life stage due to incineration during the production and use stage. All mean substitution benefits were significantly different between all the pairs of scenarios. The carbon sink ranged from 0.42 Mt $C0_2$ to 1.31 Mt $C0_2$ for the different scenarios in 2030.

The substitution benefits are indirectly included in the GHG reporting due to the avoided emissions as the result of use of HWPs. To illustrate how much emissions are avoided by substitution benefit, it should be calculated and considered, as it is important for policymakers to develop more effective policies for effectively mitigating climate change. Calculating substitution benefits would also help to plan climate-smart use of the available wood resources.

Sammendrag

I denne oppgaven var målsettingen å studere karbonsubstitusjon- og lagringsfordeler fra trebaserte produkter fra skogindustrien i dag og på mulighetene for fremtiden. Totalt fem ulike produksjonsporteføljer, senarioer, ble vurdert.

Data ble samlet fra forskjellig kilder for å bestemme karbonsubstitusjonsfaktorer og sluttbruk for trebaserte produkter. Monte Carlo-analyse ble gjennomført for beregning av substitusjonsfordelen for produksjon og bruksstadiet og for sluttstadiet. For beregning av lagringsfordelene ble metoder fra de Forente Nasjoners (FNs) klimapanel samt produksjonsdata benyttet.

Senario 1 og 2 ble definert basert på produksjonsstatistikk fra skogsektoren. For senario 1 ble gjennomsnittet av produksjonen av trebaserte produkter for de fem årene 2017 til 2021 brukt, og for senario 2 ble 2021 produksjonen benyttet. I senario 3 ble nylig etablerte eller bekreftede investeringer i produksjonskapasitet i Norge lagt til produksjonen for trebaserte produkter i 2021. For senario 4, ble ikke-bekreftede kapasitetsinvesteringsplaner fra mulige investorer lagt til. Senario 5 fokuserte på å benytte eksportert virke i senario 3 til innenlands produksjon av trebaserte produkter med høye karbonsubstitusjonsfaktorer og lenger levetid.

Senario 5 hadde den største substitusjon- og lagringsfordelen av alle senarioene. Den nylige etablerte eller bekreftede kapasiteten i senario 3 medførte betydelig økning i karbonsubstitusjonsfordelen sammenlignet med den tidligere produktkapasiteten i senario 1 og 2. Karbonbindingen i trebaserte produkter ble redusert for alle senarioene over tid. Papirprodukter og tekstiler opplevde den raskeste nedgangen på grunn av deres korte oksidasjonstid. Resultatene viste også at produksjon- og bruksstadiet bidro mer til karbonsubstitusjonsfordelen enn sluttstadiet for alle senarioer. Dette var spesielt tydelig i senario 4, som hadde den største andelen av biobrensel og pellets uten substitusjonsfordel i sluttstadiet på grunn av forbrenning i produksjon- og bruksstadiet. Alle gjennomsnittlige substitusjonsfordeler var signifikant forskjellige mellom alle parene av senarioer. Karbonbindingen varierte fra 0.42 Mt $C0_2$ til 1.31 Mt $C0_2$ for de forskjellige senarioene i 2030.

Substitusjonsfordelene er indirekte inkludert i de nasjonale klimarapporteringene ved at utslipp unngås som følge av bruk av trebaserte produkter. For å begrense effektene av klimaendringene er det viktig å beregne og vise beslutningstakerne hvor store utslipp som unngås på grunn av substitusjonsfordeler. Dette vil være med på å bidra til klimasmart bruk av de tilgjengelige trebaserte ressursene.

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1. Introduction

1.1. Background

Managed forests in Norway have a net uptake of carbon dioxides (CO_2) equivalent to around half of the nation's annual greenhouse gas (GHG) emissions (Statistics Norway, 2022a). The forests provided a carbon sink in 2020, a reservoir that stores more carbon that it releases, of about 25 Mt carbon dioxides equivalents ($CO_{2\text{-eq}}$), when including emissions and removals from harvested wood products (HWPs). Of this, the HWPs pool constituted about 0.5 Mt $CO_{2\text{-eq}}$ (The Norwegian Environment Agency et al., 2022). When trees are harvested, the biomass in them is converted into HWPs, such as paper products, sawnwood, panelboards, pellets and biofuels. The use of the forest biomass in HWPs is acknowledged to contribute to climate change mitigation by storing carbon, i.e. carbon storage benefits (Grêt-Regamey et al., 2008). Furthermore, when HWPs replace carbon intensive materials, carbon substitution benefits are achieved (Leskinen, 2018; Sathre & O'Connor, 2010). Thus, HWPs mitigate climate change via a carbon storage benefit, a material substitution benefit (a reduction in the consumption of fossil fuels in material production, transportation, etc., as a result of the substitution of other materials with HWPs), and an energy substitution benefit (the substitution of fossil fuels as a result of the energy use of HWPs) (IPCC, 2014).

Norway, like almost every other country in the world, has agreed to reduce GHG emissions, most recently that goal was enforced under the Paris Agreement (Norwegian Ministry of Climate and Environment, 2021). Forest and other land categories in Norway play an important role in the context of climate change mitigation. The Norwegian Government has set a goal to increase the harvest levels in a sustainable matter, while at the same time the aim is to achieve the long-term goals of the Paris agreement. In addition, the government aims to enhance forest growth and reduce emissions from forest and other land categories and make use of renewable forest materials when bringing the green shift into the economy. To further support sustainable development, the government aims to increase the production and use of biofuels to reduce GHG emissions from fossil fuels. By 2030, the government has set a goal to increase the use of biofuels by 40% in road transports and 30% in aviation (Norwegian Ministry of Climate and Environment, 2020).

Within the European Union's (EU) international policy regime (2018/841), forests are a part of the Land Use, Land-Use Change and Forestry (LULUCF) sector. The LULUCF regulation determine the accounting rules of how the emissions and removals will be quantified to achieve the climate target in the land-use sector. Norway is required to compare its forest-based emissions to so-called Forest Reference Levels (FRL) until 2030, as a part of the LULUCF agreement. The FRLs assume that the forest management practices carried out in the reference period (2000–2009) are continued during the compliance periods. FRLs are not forecasts or targets, but benchmarks or baseline levels for net GHG emissions calculated based on historical forest carbon stock levels, deforestation, and forest degradation rates which the future net emissions will be compared. If the carbon sink is larger than the FRLs, then the exceeding carbon sink can be sold as carbon credits to other countries or be used to compensate for carbon source in other sectors. Furthermore, if the carbon sink is smaller, due to e.g., increased harvest, then the gap needs to be accounted as emission. The gap must then be compensated by extra emission reductions in the sectors included in the Effort Sharing Regulation (e.g., agriculture, waste, transport, buildings) or covered by purchases of surplus credits from other countries aligned to the EU in the LULUCF regulation (Norwegian Ministry of Climate and Environment, 2020; Päivinen et al., 2022).

To assess the net emissions of wood use, it is required that the carbon fluxes in both the forest ecosystem and HWPs are quantified. Carbon is stored in the trees and soils of the forest ecosystem. The HWPs continue to store some of that carbon after harvest, while GHGs are eventually emitted from biomass combustion or e.g., from oxidization at landfills. Furthermore, use of HWPs could avoid fossil emissions due to material and energy substitution (Hurmekoski et al., 2020).

Norway follows the rules set by the Intergovernmental Panel on Climate Change (IPCC) when it comes to keeping track of and measuring carbon storage and carbon substitution (IPCC, 2014). In the reporting of GHG inventories, all annual net emissions or emissions savings are converted to $CO_{2\text{-eq}}$ since CO_2 is the most important and well-known GHG. As a tool to monitor the climate change mitigation, Norway annually reports the GHG emissions in the National Inventory Report (NIR) submitted to United Nations Framework Convention on Climate Change (UNFCCC) and EU (Norwegian Ministry of Climate and Environment, 2021).

While the positive role of forests in climate change mitigation is generally well perceived, the contribution of wood products to mitigation has received less attention. Current national reporting of GHG emissions to the UNFCCC and related processes does not attribute the substitution benefits of wood-based products directly to the forest sector. However, this information is important when developing optimal strategies on how forests and the forest sector can contribute to climate change mitigation (Leskinen, 2018). To my knowledge, there has not been conducted any previous studies in Norway where carbon substitution benefits from HWPs have been explored in terms of different product portfolios where the main products from forests were assessed.

The harvesting level in Norway might change in the future. On the one hand, there is an increasing focus on biodiversity, and certifications within forestry. For example, the new Norwegian PEFC standards implemented March 1st, 2023, demands mapping of important biotopes to insure the habitat of endangered species for all forest properties over 5 hectares. In addition, all forest estates of more than 150 hectares are required to set aside 5% of the forest area for biological important habitats (PEFC, 2023). Thus, the increased focus on biodiversity and certification will reduce the forest area where an active forest management can be applied, and the annual harvests might decrease. On the other hand, the demand for wood for HWPs is increasing and contributes greatly to the to the nation's green economy (Government.no, 2014). The annual volume increment has been larger than the annual harvested levels since the 1950s, although the harvesting levels to some extent have increased the last decade (Hylen, 2021). The result of this has been a large build-up of standing volumes in Norwegian forests, which potentially may supply new forest industries with the raw material needed to produce more HWPs than today.

The point of departure for estimating the HWPs is to determine the current forest industry production for Norway. For every HWP manufactured, an estimate is made of its production and a carbon substitution factor (CSF) is applied to each product. The CSF reflects the amount of carbon emission generated if a non-wood product was used instead of the HWP and is estimated based of alternative materials that could been used for the same purpose.

A few studies have previously been focusing on changes in product portfolios and benefits of substitution factors on net emissions of carbon. Hurmekoski et al. (2020) analyzed how a realistic product portfolio for future wood use would develop with a decline of graphic paper consumption due to electronic media and the emerge of wood-based products, and how a more diversified market structure would impact the net emission of the Finnish forestry. Soimakallio et al. (2016) and Suter et al. (2017) both emphasized the importance of taking the full life cycle of different materials and technologies into consideration when identifying and using low emission alternatives. While HWPs might substitute more carbon than other materials it is important to ensure that increased wood utilization is sustainable and does not negatively affect the forest ecosystem or other land use. Using forest biomass for substitution can result in reduced emissions from materials emitting large amounts of carbon. On the other hand, substitution can happen at the expense of carbon sequestration in forest, creating a need for a holistic approach that balances multiple objectives, including climate change mitigation and sustainable development (Soimakallio et al., 2021).

1.2. Objective

The thesis will examine the carbon substitution and storage benefits from HWPs produced by the forest-based industries in Norway today and those potentially produced in the future. To achieve this, five different scenarios were developed.

Scenarios 1 and 2 were based on forest sector production statistics. Scenario 1 represents the average production from 2017 to 2021 while scenario 2 is based on the production level from 2021.

Scenarios 3 and 4 were created based the information from forest industry investment plans found in the literature. In scenario 3, recently established or confirmed production capacity investments in Norway were added to the production of HWPs in 2021. In scenario 4, also non-confirmed capacity investment plans aired by the potential investors were added. In scenario 5, the exported wood in scenario 3 was used for domestic production of HWPs with increased carbon substitution factors and longer life spans. This scenario was presented as an illustrative example to highlight how HWPs can be utilized to prioritize substitution. Thus, the following scenarios were considered:

1. Average production for the five years 2017 to 2021
2. 2021 production
3. 2021 production + new confirmed since 2022
4. 2021 production + confirmed since 2022 + potential production
5. 2021 production + confirmed since 2022 + favorable production

There is an obvious uncertainty related to the end-uses of semi-finished products produced as well as their substitution factors. Thus, Monte Carlo simulations were used to assess the effects of uncertain parameters and how these influence the results.

2. Methods

Calculation of carbon storage, substitution benefits and uncertainty will be discussed in the subchapters below.

The main allocation of harvested wood into HWPs is illustrated in Figure 1. Saw logs are produced into sawnwood, plywood and veneer often used for construction, furniture, and interior. Pulpwood, sawmill chips, and other sawmill residues are produced to panel products, like particle board, and pulp and paper products as well as chemicals. The logging residues may be collected and used as feedstock for energy or production of biofuels. The products can also be redistributed in other ways. In principle, sawlogs could also be used for pulp making and pulpwood used for energy, but that is most often not economical.

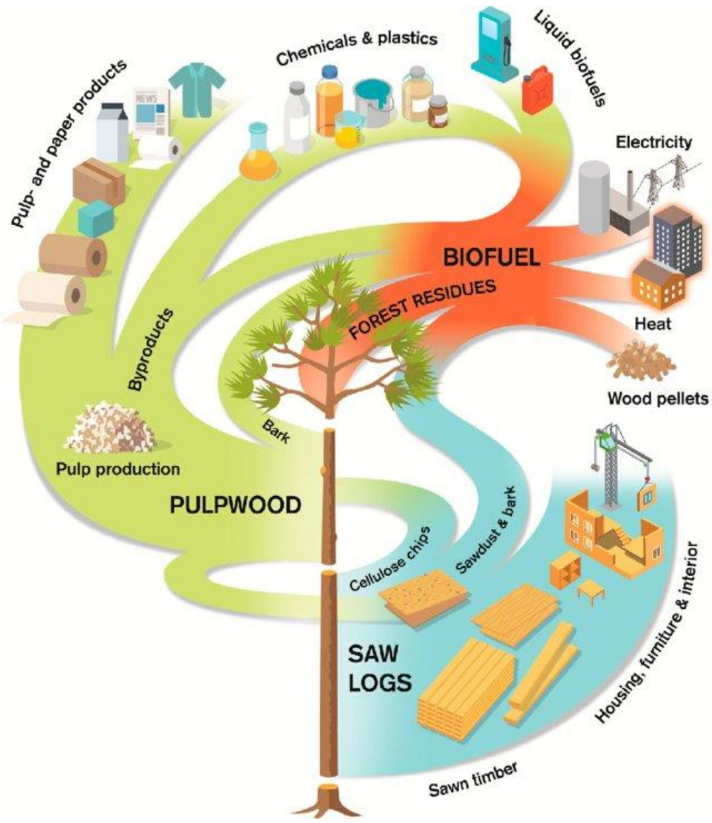

Figure 1: Allocation harvested wood into harvested wood products (Source: Sikkema et al. (2017))

2.1 Calculating the carbon sinks of harvested wood products.

Harvested wood products store carbon at least for a certain time period. If the amount of carbon entering a HWP pool exceeds the amount leaving it, the pool acts as a carbon sink, else it is a source. There are several alternative methods for calculating the carbon sinks and sources of HWP pools.

The approaches "atmospheric flow" and "simple-decay" are based on CO_2 fluxes to and from the atmosphere from HWPs within a nation's boundaries. The "atmospheric flow" approach tracks the flow of CO_2 to and from the atmosphere as a result of HWP production, use and disposal (IPCC, 2006a). While the "simple-decay" approach estimates the carbon loss from HWPs through decay over time. The "stock-change" approach is similar to the "production" approach in the way that both approaches account the carbon stock within a defined pool. The difference between the approaches is that the "production" approach focusses on the origin of the production, i.e., the production within a country while the "stock-change" approach tracks the carbon change within the pool for a specific time period (IPCC, 2006a; IPCC, 2019).

In this thesis, the "production" approach which follows the so-called "Tier 2 method" from the IPCC, is used to quantify carbon sinks or sources for forest industry products (IPCC, 2006b). In Norway this method is used when reporting HWP carbon stocks to the UNFCCC and the "Tier 2 method" refers to the complexity and accuracy of the method and data (IPCC, 2019; The Norwegian Environment Agency et al., 2022). This approach focuses on where the HWPs are produced regardless of where they are consumed.

In the current GHG reporting, which follows the regulations of the Paris agreement, HWPs are calculated using exponential decay, also called first order decay. In this calculation the decay rates are calculated using default life spans and carbon contents (Norwegian Ministry of Climate and Environment, 2020).

To calculate the carbon stock for a year, let *C(i)* denote the carbon stock in the beginning of the year *i,* let ΔC denote the change in this stock and let *C(i+1)* be the carbon content at the end of the year. Using first order decay, *k* is calculated from information about lifetimes of the products, and defined as *k=ln(2)/HL*, where *HL* is half-life of the HWP pool in years (IPCC, 2006a). Furthermore, let *Inflow(i)* denote the new HWP produced during year *i*. This *Inflow* is calculated as the year's new HWP multiplied by the carbon conversion factor. Accordingly the change in carbon stock can be calculated from the Equations 1 and 2 below (IPCC, 2006b):

$$\Delta C(i) = C(i+1) - C(i) \quad \text{(IPCC, 2013)}, \qquad [1]$$

$$C(i+1) = e^{-k} \times \ C(i) + \left[\frac{(1-e^{-k})}{k}\right] \times Inflow(i) \qquad [2]$$

To calculate *Inflow,* let $HWP_p(i)$ indicate the production of HWP in a category in year *i* (m^3 or t) using domestically harvested wood and let $f_R(i)$ denote the share of woody feedstock based on the product class $_R$, which is either sawnwood, wood-based panels or paper and paperboard. In addition, textile fiber was added as its own product class since it is not included in the "Tier 2 method" of the IPCC guidelines. Let *cf* denote the conversion factor for the HWP used to convert the production volume for each product into carbon. These conversion factors are somewhat regional/country-specific, as they are depending on e.g. wood-density (IPCC, 2013). The information is often not easily available, specifically when it comes to finished commodities, but information can sometimes be found in life cycle inventory data which form the basis for life cycle assessments (ISO, 2006a; ISO, 2006b).

Finally, let f_{IRW}, $f_{PULP}(i)$ *and* $f_{RecP}(i)$ denote the subcategories called "industrial roundwood", "wood pulp" and "recovered paper", respectively. These categories are used to calculate the share of woody feedstock of the total production volumes, along with the recovered paper utilization rate *q* (IPCC, 2013). Then the *Inflow* can be calculated using the equations 3 and 4 below.

$$Inflow(i) = HWP_P(i) \times f_R(i) \times cf \qquad [3]$$

Where:

$$f_R(i) = \begin{cases} f_{IRW}(i) & \text{for HWP categories sawnwood and woodbased panels} \\ (f_{IRW}(i) \times (1-q) \times f_{PULP}(i)) + q \times f_{RecP}(i) & \text{for HWP categories paper and paperboard.} \end{cases} \qquad [4]$$

To estimate the changes in carbon pool, an estimate of the size of the current pool is necessary. To overcome the large uncertainties related to that, the calculations start from the earliest year when data on production of HWPs can be found in FAOSTAT database (FAO, 2023). For most countries, including Norway, the calculations are initialized from year 1960 (FAO, 2023; IPCC, 2013). The stock of the HWP is assumed to be at steady state at the initial time (t_0 =1960), where $\Delta C_{(1960)}$ is assumed to be 0. The initial carbon stock $C_{(t0)}$ for a HWP category is based on the average inflow of carbon to the pool during the first five years for which statistical data is available (IPCC, 2013).

2.2. Calculating the substitution benefits of harvested wood products

The substitution benefits related to forest industry production are estimated by multiplying the quantities of HWPs produced with their so-called substitution factors. The carbon substitution factor (*CSF*) indicates how much carbon is saved by substituting a non-wood product with a wood product serving the same purpose. It can be calculated as (Sathre & O'Connor, 2010):

$$CSF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}}, \qquad [5]$$

where $GHG_{non\text{-}wood}$ and GHG_{wood} are the GHG emissions resulting from using non-wood products and wood products, respectively. WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood for these two alternatives, respectively. Mostly both the nominator (emissions) and denominator (wood content) are expressed in terms of carbon, so that the unit for CSF is tC/tC, but also other units are occasionally used. Equation 5 allows the possibility that also the “non-wood” products contain some wood (Leskinen, 2018). A positive CSF means that the HWP causes less GHG emissions than the product it is replacing.

Carbon substitution factors are context specific. For instance, a wood-product substituting a product made of another material (e.g., steel) most likely have a different carbon substitution factor if the product is used for construction or making furniture (Myllyviita et al., 2021).

The substitution factors are often split to be assessed into two stages in the product lifetime. The substitution benefit obtained during the stage of production and subsequent use of HWP will in this work be referred to as production and use stage. The substitution benefit for the end-of-life stage will be here be called by end-of-life. The end-of-life benefit is most often obtained from incinerating the HWP for energy when no other uses are feasible (Bache-Andreassen, 2009; Hurmekoski et al., 2020).

2.3. Uncertainty

There are large uncertainties in both the carbon substitution factors between wood and various alternative materials in their end-uses as such, and in the end-uses of forest industry products. Reliable statistics on current material usage for various purposes, e.g., furniture or window frames, are lacking. Also, even if there were statistics, substitution is related to something that does not or did not happen, and thus cannot be observed: it is not possible with certainty to know which material would have been used if the wooden product had not been available. Consequently, it is necessary to define assumptions for the HWP end-uses and materials they substitute. The assumptions are uncertain, and this uncertainty influences the estimated carbon benefit of the product portfolios. A Monte Carlo analysis was therefore applied to assess how the uncertainty may impact the results.

The parameter ranges applied for the HWP end-uses, and the carbon substitution factors are presented in Section 3.3.

The results were presented as density plots and cumulative density plots to show the resulting substitution benefits obtained from the different state-of-natures from the Monte Carlo analysis and mean, standard deviations and median results were calculated. Furthermore, the mean values obtained for the different scenarios were tested if they were statistically different by means of Welch's t-tests. The Welch's t-test is also known as unequal variances t-test and is used to test whether the means of two population are equal. For the statistical computing and plotting the R software was used (R Core Team, 2023).

3. Material

3.1. Product portfolios according to the different scenarios

Carbon storage and carbon substitution benefits were calculated for the product portfolios in scenarios 1 to 5 as shown in table 1. These alternatives regarding use of industrial roundwood harvested in Norway include existing, confirmed, potential, and favorable forest industry production volumes as described below in more detail. Generally, it is important to note that a considerable amount of fuelwood (2 Mm^3) is harvested and used in Norway (Statistics Norway, 2022b). This study, however, considers carbon storage and substitution benefits of HWPs produced by the wood-based industries only.

For scenarios 1 and 2, the data used for previous production volumes were obtained from FAOSTAT forestry data base (FAO, 2023). Scenario 3 includes, in addition to the production from 2021, the capacity of the recently established productions after 2021 and the capacity of the industries confirmed to start within the next years. Potential capacity investments that had been aired but for which no final investment decision had been made was included to scenario 4 only. The sources for the confirmed and potential capacities were various, including press releases from the companies and articles from the magazine "Norsk Skogbruk", which is a magazine focusing on the Norwegian forest sector. One important additional source was the documents from Prosess21 (Prosess21, 2020). To provide information on which projects were included into the scenarios 3 and 4, the individual projects are detailed in table A1 and A2 in the Appendix. For some of the confirmed and potential investments, only information about the amount of input raw material required for the future production was available. In cases where the companies have not stated the output of finished or semi-finished products, conversion factors were used to calculate the amount of output product. These factors were reported by FAO et al. (2020).

In scenario 3, the new confirmed forest industry production capacity was added to the 2021 production. The confirmed sawnwood capacity investments amount to 630 000 m^3, whereas kitchen and sanitary paper production will increase by 25 000 tons, and white pellet production by 55 000 tons (see appendix, Table A1). Also, HWPs that will be new in Norway such as plastic pellets (CEBICO) (see appendix, Table A2) enter the production palette. In scenario 3, the net export of sawlogs was assumed to be reduced to 379 000 m^3 due to increased sawnwood production, while the net exports of pulpwood (possibly partly in form of sawmill chips) were increased to 2 Mm^3, due to the increase in domestic sawnwood production that also increases the sawmill residues (FAO et al., 2020). These residues can be used as raw material for many of the products in this scenario. In addition, 200 000 m^3 logging residues are used to produce black pellets.

In scenario 4, new potential forest industry production capacity was added to the confirmed production capacity in scenario 3. In this scenario, Bleached Chemi-Thermo Mechanical Pulp (BCTMP) has a potential to increase further with 375 000 tons. Also, Medium Density Fiberboard (MDF) may enter the product palette with a capacity which was here assumed to be 168 000 m^3 (see appendix Table A2). The increased production of paperboards was assumed to be produced by recycled paper. In addition to this, biofuels were included into the production palette: bio-oil and bioethanol. Also bio coal would be obtained as a biproduct from the biofuel production, but it was not included in this analysis (Biozin, 2021; Biozin, 2023). Even if some of the potential production depends on the results from, for example, demo plants before a full-scale production can start – such as plastic pellets (CEBICO) from Norske Skog – several of these investments remain uncertain. However, these investments are heavily supported by Shell, Innovation Norway, Viken Skog, and other big actors with the financial capacity to launch the new production. In scenario 4, about 3.6 Mm^3 of additional raw input material was needed to produce MDF, BCTMP, plastic pellets and biofuels (appendix, Table A2). Thus, in scenario 4 all the net exports of pulpwood in scenario 3 were redirected into domestic production. In addition, the harvests of pulpwood were increased by 1.6 Mm^3.

In scenario 5, HWPs with increased carbon substitution factors and longer life spans were produced. This scenario was constructed by maintaining the same harvest levels for sawlogs and pulpwood as in scenario 3. The net wood exports of scenario 3 were allocated for use in the domestic forest industries. Thus, all sawlogs were used for additional sawnwood production in Norway. The net sawlog export was redirected to increase the sawnwood production in Norway by about 0.18 Mm^3, MDF was set to have the same production as in scenario 4, and 0.32 Mt of wood-based textile fibers was added to the production palette. The resulting increase in sawmill residues, and the net exports of pulpwood in scenario 3, was split between panels (267 000 m^3 sawmill residues) and textiles (2 Mm^3 chips and pulpwood) (see appendix Table A3).

Table 1: Forest industry production in Norway in scenarios 1 to 5.

		Scenario[d]				
Production[a]	**Unit**	**1**	**2**	**3**	**4**	**5**
Paper and paperboard:	Mt	1.06	1.01	1.06	1.11	1.06
-Printing and writing papers	Mt	0.91	0.84	0.84	0.84	0.84
-Paper and paperboard for packaging	Mt	0.13	0.15	0.15	0.20	0.15
-Household and sanitary papers	Mt	0.02	0.02	0.05	0.05	0.05
Net export of pulp incl. BCTMP	Mt	0.14	0.15	0.15	0.52	0.15
Dissolving pulp	Mt	0.15	0.17	0.17	0.17	0.17
Sawnwood	Mm^3	2.70	2.81	3.45	3.45	3.64
Particleboard	Mm^3	0.29	0.32	0.32	0.42	0.32
Fiberboard	Mm^3	0.17	0.18	0.18	0.18	0.18
Medium Density Fiberboard (MDF)	Mm^3				0.17	0.17
Isolation materials[b]	Mt	0.04	0.04	0.04	0.04	0.04
White pellets	Mt	0.08	0.15	0.21	0.21	0.21
Black pellets	Mt			0.07	0.07	0.07
Plastic pellets	Mt			[e]	0.05	
Bio-oil	Mm^3				0.22	
Bioethanol	Mm^3	0.02	0.02	0.02	0.07	0.02
Specialty lignin[c]	Mt	0.17	0.17	0.17	0.17	0.17
Textiles	Mm^3					0.32
Net export wood, of which	Mm^3	3.02	3.32	2.38	0.38	
- sawlogs	Mm^3	1.29	1.65	0.38	0.38	
- pulpwood	Mm^3	1.73	1.67	2.00		

Note: Paper industry in Norway also uses some imported pulp, therefore only net exports (export-import) of pulp were considered. Dissolving pulp production in 2020–2021 was approximated by exports (FAO, 2023).

[a] FAO (2023). [b] Hunton Fiber As (2019). [c] Klitkou (2013)

[d] For description of the scenarios see text.

[e] 300 tons produced.

3.2. Carbon storage parameters

Information about yearly carbon inflow and half-life were used to track the carbon in the HWP pool. For half-lives and carbon contents, the default values of the IPCC (2013) were used (Table 2). Hence, the results will be comparable with the Norwegian GHG reporting for UNFCC (Norwegian Environment Agency et al., 2020). In addition to the three main product groups, paper, panels, and sawnwood used for the UNFCC carbon accounting, the carbon storage for wood-based textile fibers was considered. Following Hurmekoski et al. (2020), the same lifetime as for paper was assumed for textiles. The carbon content was assumed to be the same as for paper. Eventually, pulp for textiles is rather similar to pulp for paper, and the value used (0.386 tC/t) is an average of the values reported by Shen and Patel (2010) and Schultz and Suresh (2017). The productions of biofuels and pellets were not added to the carbon storage calculations, because the products were expected to be burned within one year and will therefore not offer any carbon sink.

Table 2: Carbon storage parameters in tC/output unit and half-life for HWPs.

HWPs	Output unit	Carbon content (tC/unit)	Half-life	Source[a]
Sawnwood	m^3	0.229	35	1
Wood-based panels	m^3	0.269	25	1
Paper and paperboard	t	0.386	2	1
Wood-based textiles	t	0.386 [b]	2	2

[a] 1. IPCC (2013), 2. Hurmekoski et al. (2020)
[b] Shen and Patel (2010) and Schultz and Suresh (2017)

When calculating the carbon storage, it was assumed that the products enter the carbon storage in the same year as their production starts. For scenario 3, the total increase in sawnwood was 630 000 m^3. In total 459 000 m^3 of this was added to the carbon storage in 2022, 81 000 m^3 was added in 2023, 31 000 m^3 was added in 2024, and 63 000 m^3 was added in 2025. For the sawnwood production that started in mid-2023, half of the production was added in 2023 and the rest was added in 2024. All the paper added to scenario 3 was added in 2026 (see appendix Table A1).

For scenario 4, more production was added in 2026 into the case of scenario 3 described above. More precisely, 168 000 m^3 of MDF and 10 000 m^3 of particle board was added into panels, and 50 000 tons of paper board were added into paper. Scenario 4 also involved new production capacity of BCTMP, which was added to the Norwegian reporting of paper products to UNFCCC (IPCC, 2013). Net pulp exports were however excluded from consideration. For scenario 5, sawnwood, panel and textile production increased in 2022 by 190 000 m^3, 168 000 m^3 and 320 000 tons, respectively. This was added to the scenario 3 production (see Table 1).

3.3. Assumptions and data employed to calculate carbon substitution benefits

Resent reviews (Hurmekoski et al., 2021; Leskinen, 2018; Suter et al., 2017) show a large variation in carbon substitution factors for HWPs. The carbon substitution factors are calculated based on eq. 5. For a given wood-based product, the substitution factor may vary considerably depending on which non-wood product it replaces. As an example, Hurmekoski et al. (2020) employed a production stage substitution factor of 0.8 tC/tC for plywood when used for substituting non-wood materials in construction. This factor is considerably smaller than the respective substitution factor proposed by

Knauf et al. (2015) when plywood was substituting aluminum, glass fiber and plastic in construction (1.62 tC/tC). Also, the end-uses of the harvested wood product affect the substitution benefits obtained. In most cases, there is no statistics available that give precise answers to how the use of a specific HWP is divided between its end-uses and which materials are replaced to which degree. There is for instance no solid data available on how much of the sawnwood produced in Norway that is used to structural and non-structural construction, furniture making, packaging applications and other uses. However, the division and materials replaced in these end-uses affects the substitution benefits of sawnwood production considerably. To account for the many uncertainties related to the substitution factors, the end-uses of the products, and materials replaced, ranges of plausible values were defined to these uncertain parameters (Defined below). When calculating the substitution benefits, Monte Carlo simulations were used to draw parameters from the uniform distributions given by the ranges. In the following, the assumptions made on carbon substitution factors, end-uses, and materials replaced are discussed in more detail.

3.3.1. Assumptions on substitution factors

The substitution factors (Eq. 5) applied in this study (Table 3) were collected from various former studies. Kallio et al. (2023) provided useful guidance for most of the parameters. However, they did not cover all the products considered. The references for the chosen factors for the production and use stage are provided in table 3. For the cases where no intervals are presented in table 3, factors for the production and use stage were assumed to have a variation of ±20%. The end-of-life factors are described below table 3 and assumed to have a variation of ±10% around their assumed default values.

For sawnwood used for structural and non-structural construction, the CSFs reported by Hurmekoski et al. (2020) and Leskinen (2018) were applied. For sawnwood used for construction, 0.9 tC/tC was used as a default value for production and use stage as in Hurmekoski et al. (2020). Paper products other than those used for packaging and wrapping were assumed to have CSF of 0 tC/tC in the production stage as in Hurmekoski et al. (2020). Additionally dissolving pulp was assumed by the author to have a CSF of 0.15 tC/t. Most common use for dissolving pulp globally is to produce textile fibers (Kallio, 2021). The Norwegian textile production, however, ended in the 1980s (Klitkou, 2013). Instead, dissolving pulp produced in Norway was used for various specific purposes as vanillin and pharmaceuticals (Klitkou, 2013), for which there are no CSF estimates available. Paper and paperboard used for packaging and wrapping purposes were assumed to substitute plastic, glass, and metal packaging, and their CSF was assumed to be 1.4 tC/tC following Hurmekoski et al. (2020).

It was assumed that white pellets substitute heating oil and coal, and a CSF range of 0.355 – 0.436 tC/t was used. The figures were calculated from the energy contents and emission factor of the heating oil and coal (Saracoglu & Gunduz, 2009; Statistics Finland, 2023). Black pellets were assumed to substitute coal in power plants where the producer (Arbaflame, 2022) reported the emissions of pellets to be 90% smaller than those of coal, making the CSF range of 0.45 – 0.49 tC/t (Statistics Finland, 2023).

Pellets for making plastic had a CSF 1.62 tC/t according to information provided by their producer (Norske Skog, 2023). That was used as a maximum CSF, while the minimum was set to be 0.97 tC/t, which is 40% smaller than the maximum CSF. The minimum value was set to be cautious as there was no independent estimate available to verify the value.

The CSF used for the production stage of particle board for furniture substituting glass was assumed to be 0.7 tC/tC. This was based on Suter et al. (2017), where the CSF was reported in tC/m^3 wood used. The substitution factor was therefore multiplied by 1.5 m^3 to converted into tC/m^3 product (FAO et al., 2020). Then it was multiplied by the amount of carbon (0.269) per m^3 for the CSF to have the unit tC/tC (IPCC, 2013). Fiberboard was assumed to have a CSF with the range -0.258 – 1.94 tC/tC, due to the wide range in CSFs found for this product (Rüter, 2016; Trømborg & Sjølie, 2011).

To find the carbon substitution factor for bioethanol, gasoline was used as a reference fuel. The emissions from gasoline are 2.36 $tCO_{2\text{-eq}}/m^3$ (EIA, 2022). Per volume unit, bioethanol contains about 33% less energy than gasoline (EIA, 2022). The maximum emission saving for using bioethanol is based on these numbers, and to achieve these carbon substitution factors, emissions in the production stage of these two fuels should be equivalent. The emission savings for ethanol are assessed to be 82% of the emissions of fossil fuel based gasoline (Eurpean Parliament, 2018). This has been taken into account, when calculating the carbon substitution factors, by setting the minimum value for the carbon substitution factors to 82% of the emission savings to gasoline and the maximum value to have the same emission savings as fossil fuel-based gasoline.

The production of 100 000 m^3 of bio-oil by Silva Green fuel at full scale is estimated to lead to a reduction of 250 000 tCO_2/unit of Norwegian GHG emissions (AFRY, 2023). This would provide a carbon substitution factor estimate of 2.5 tCO_2/m^3, which is close to the average emissions of gasoline and fossil diesel. The Biozin bio-oil project, is estimated to yield 2.57 Mt CO_2 savings in the operations first ten years (Biozin, 2022). The annual production level of pyrolysis oil is set to 120 000 m^3, which corresponds to a carbon substitution factor of approximately 2.1 tCO_2/m3. Due to the lack of information on the Silva Green and Biozin projects and their reference fossil fuels, these numbers were used as min and max values for bio-oils. All carbon substitution factors for biofuels and bio-oil were then multiplied by 12/44 (mass ratio of C/CO_2) to be converted into tC/unit (Appendix, Table A4).

Table 3: Carbon substitution factors (CSF) for harvested wood products (HWPs) excluding the end-of-life stage.

HWP by end-use	Non-wood product substituted	Default CSF[a]	Unit	Source[b]
SAWNWOOD				
Structural construction	Not specified	0.9	tC/tC	1
Non-structural construction	Not specified	1.2	tC/tC	2
Furniture	Not specified	0.9	tC/tC	1
Packaging	Not specified	1.1	tC/tC	2
Other	Not specified	0.7	tC/tC	2
PAPER AND PAPERBOARD				
Printing and writing papers, incl. newsprint	Not specified	0	tC/tC	1
Tissue papers	Not specified	0	tC/tC	1
Dissolving pulp	Pharmaceuticals/Vanillin	0.15	tC/t	[c]
Paper and paperboards used mainly for packaging	Plastic, glass, and metal packaging	1.4	tC/tC	1
PARTICLE BOARD AND MDF				
For construction	Various	1.1	tC/tC	3
For furniture	Glass	0.7[d]	tC/tC	4
FIBERBOARD				
Fiberboard/hardboard		[-0.258–1.94][e]	tC/tC	5, 6
INSULATION MATERIAL				
Blown in	Mineral wool	[2.91–3.77][e]	tC/tC	5, 7
Board form	Mineral wool	[3.14–9.24][e]	tC/tC	5, 7
MANMADE CELLULOSIC FIBRES FOR TEXTILES				
	Oil-based fibers	1.24	tC/t	8
	Cotton	0.7	tC/t	9
OTHER PRODUCTS				
White pellets	Heating oil and coal	[0.35–0.43]	tC/t	10
Black pellets	Coal	[0.45–0.49]	tC/t	11
Bioethanol	Motor gasoline	[0.35–0.45]	tC/m^3	1
Bio-oil	Fossil fuel	[0.57–0.68]	tC/m^3	12
Lignin as adhesive	Phenol for adhesives	0.21	tC/t	5
Plastic pellets (CEBICO)	Thermoplastic	[0.97–1.67]	tC/t	13

[a] If range not defined in brackets, factors for the production and use stage were assumed to have a variation of ±20% around their assumed default values. The CSFs were reported identically to that of their original studies, which resulted in variations in the number of decimals.

[b] Sources: 1. Hurmekoski et al. (2020), 2. Leskinen (2018), 3. Knauf et al. (2015), 4. Suter et al. (2017), 5. Rüter (2016), 6. Trømborg and Sjølie (2011), 7. Kallio et al. (2023), 8. Rüter (2016), 9. Shen et al. (2010), 10. Saracoglu and Gunduz (2009), 11. Arbaflame (2022), 12. AFRY (2023), 13. Norske Skog (2023)

[c] Assumed by the author.

[d] Figure of Suter et al. (2017) was converted to tC/tC assuming the use of wood 1.6 m^3/m^3 and carbon content of 0.269 tC/m^3 of particle board.

[e] Converted into tC/tC but reported in other units in the literature.

As discussed earlier, Norway is a net exporter of industrial roundwood (Table 1) and the wood is mostly exported to Sweden and Germany (Landbruksdirektoratet, 2023; Steinset, 2021). To calculate the carbon substitution benefit for the exported roundwood originating from Norwegian forests, it was assumed that pulpwood was used for paper production and sawlogs were used to sawnwood production in the countries of destination. To calculate the substitution benefit for the exported wood, the net exports were converted into tons of mechanical pulp and cubic meters of sawnwood by dividing the net export volume with conversion factors of 2.6 m^3/t and 2.0 m^3/m^3 for pulp and sawnwood, respectively (FAO et al., 2020). For this amount, the same carbon substitution factors for paper and sawnwood as in Norway, or more precisely, the distributions of them, were applied to calculate the substitution benefit. The substitution benefits obtained when producing forest industry products from Norwegian roundwood abroad were reported separately from the substitution benefits of the products produced in Norway. This was done in order to be consistent with the calculation of carbon storage benefits that were only calculated for domestic production in Norway.

It is assumed that all wood products, as far they can be recovered, can be used for energy at the end of their lifespan. This is the current practice in Norway, as well as in other countries such as Finland, as landfilling of biodegradable material is prohibited (Bache-Andreassen, 2009; Hurmekoski et al., 2020). A widely used substitution factor for HWPs at their end-of-life stages has been 0.8 tC/tC (Pukkala, 2014). However, it can be expected that substitution factors have decreased with the declining amounts of fossil energy used and the increasing share of renewable energy. Following Hurmekoski et al. (2020), the end-of-life substitution factor was given a default value of 0.6 tC/tC. However, a $\pm$10% variation was applied to it. Since toilet paper does not substitute any product only tissue paper has a CSF in the end-of-life stage. Manmade cellulosic fibers for textiles were assumed to have an end-of-life substitution factor of 0.09 tC/t product (Rüter, 2016). Additionally, lignin as adhesive was assumed to have an end-of-life substitution factor of 0.34 tC/t product (Rüter, 2016). Neither dissolving pulp, pellets nor biofuels were assumed to have any end-of-life substitution factor because they are burned during the consumption stage.

3.3.2. Assumptions on end-uses and materials replaced.

As can be seen from table 4, for some of the products, the CSFs applied depend on their end-uses and/or materials substituted. In such cases, further assumptions on end-use were needed.

Considering sawnwood, construction was the largest end-use segment. Treindustrien (2021) reported that 75% of the sawnwood produced in Norway was used as building materials ("byggtre"), while the rest was sold as semi-finished products ("halvfabrikata"). It was assumed that 70-80% of all sawnwood was used for construction. Leskinen (2018) reported that from overall sawnwood, 50% is used for construction, which referred to structural construction. The share of structural construction accounts to about 50% of the total amount of sawnwood products when 60-70% of the construction is produced as structural construction. It was assumed that 2-4% of sawnwood was used to production of furniture based on numbers from Hurmekoski et al. (2020). Of all sawnwood, 19% was assumed to production of packaging while 3% was assumed to production for other uses, as in Sandberg et al. (2014).

Suter et al. (2017) reported the distribution of particle boards into production for construction and furniture to be 60% and 40%, respectively. Here, it was assumed that 50-70% of particle boards were used for construction while the rest was used for furniture production. MDF was assumed to have the same distribution as particle board. For the insulation materials, the production of blown in insulation material and insulation material in board form was split in two (Bjørheim, 2019).

When it comes to household and sanitary paper, it was assumed that 75-85 % was papers with no incineration potential in the end-of-life.

Table 4: Assumptions made on the end-uses and/or materials replaced by the harvested wood products produced in Norway.

HWP by end-use	Division of end-use	Sources[a]
SAWNWOOD		
Construction	***70–80%***	1
Of that, structural	60–70%	2
Of that, non-structural	Rest 30–40%	
Furniture	***2–4%***	3
Packaging	80–90% of the rest	
On average 19% of all sawnwood	After construction and furniture	4
Other uses		
On average 3% of all sawnwood	Rest	4
PARTICLE BOARD		
Construction	50–70%	5
Furniture	Rest	5
MDF		
Construction	50–70%	5
Furniture	Rest	5
INSULATION MATERIAL		
Blown in	50–60%	6
Board form	Rest	6
HOUSHOLD AND SANITARY PAPER		
Tissue/kitchen paper	15–25%	[b]

[a] 1. Treindustrien (2021), 2. Leskinen (2018), 3. Hurmekoski et al. (2020), 4. Sandberg et al. (2014), 5. Suter et al. (2017), 6. Bjørheim (2019)
[b] Assumed by author.

3.3.3. Calculating the substitution benefits

For a given production scenario, the total substitution benefits, or more precisely, the distribution of total substitution benefits, were calculated. Random draws were carried out to prepare 5000 state-of-natures using Microsoft Excel 365. In each state-of-nature, for a given product, sawnwood for instance, the division of its end-uses was drawn from distribution in table 4, if end-use division was relevant. A respective amount from the production in the scenario was allocated into these uses and expressed in units consistent with the relevant substitution factors (Mt C, Mm^3, or Mt). For each end-use, a respective CSF in the production and use stage and the end-of-life stage was drawn from their distributions described in section 3.3.1 (see also Table 3). For each state-of-nature, product wise substitution benefit was then calculated by multiplying the amounts of production in various uses by their CSFs and summing over the uses. The total substitution benefit in a state-of-nature was obtained by summing over substitution benefits for all individual products.

4. Results

4.1. Carbon storage and changes in carbon stocks

The annual changes in carbon storage for the five scenarios for the years 2020 to 2050 were calculated. Figure 2 shows the changes in carbon sink as a sum of the product categories, sawnwood, panels, paper, and textiles, during the years for each scenario. Negative numbers indicate a carbon sink and positive numbers indicate a carbon source.

Scenarios 1 and 2 were based actual production quantities as the average of the years 2017 to 2021 and the 2021 production, respectively. The results were very similar, however, scenario 2 gave more carbon storage than scenario 1 due to a larger production in 2021 compared to the previous years (Figure 2). The total harvest levels used as input for scenarios 1 and 2 were 10.8 Mm^3 and 11.5 Mm^3, respectively.

The scenarios 3, 4, and 5 were developed based on scenario 2 and assumptions regarding future production capacities. In scenario 3, where confirmed new production capacities were added to the 2021 production, the carbon storage was 0.52 Mt CO_2 (95%) larger compared to scenario 2 in 2027. In scenario 4, where potential new production capabilities were added to scenario 3, the carbon storage was 0.53 Mt CO_2 (49%) larger in 2027 and 0.09 Mt CO_2 (14%) larger in 2050 than scenario 3.

The volume of industrial roundwood harvests were the same in the scenarios 3 and 5, but the net export and forest industry production differed. In contrast, scenario 4 had an increased wood input in terms of industrial roundwood of approximately 1.6 Mm^3. Some of the products in scenario 4 were made from return wood, meaning that the increased production of these products did not contribute to an increased wood consumption.

In scenario 5, where the exported wood in scenario 3 was used for domestic production of HWPs with increased carbon substitution factors and longer life spans, the carbon sink was 0.39 Mt CO_2 (36%) larger in 2027 compared to the carbon sink in scenario 3. However, the increase in carbon sink quickly dropped and was down to 0.17 Mt CO_2 (25%) in 2050. Scenario 5 was the scenario storing the most carbon, however, the export was reduced to zero and greater volumes of sawnwood and panels were produced. Furthermore, by using wood for domestic production instead of exports, the carbon storage of the HWPs is included in the Norwegian GHG reporting.

The carbon sink in HWP stock ranged from 0.42 Mt $C0_2$ to 1.31 Mt $C0_2$ in 2030 across the five scenarios compared. These numbers are in line with NIR (The Norwegian Environment Agency et al., 2022) and the FRLs of 2021-2025 (Norwegian Ministry of Climate and Environment, 2020) reporting 0.45 Mt $C0_2$ and 1.23 Mt $C0_2$, respectively.

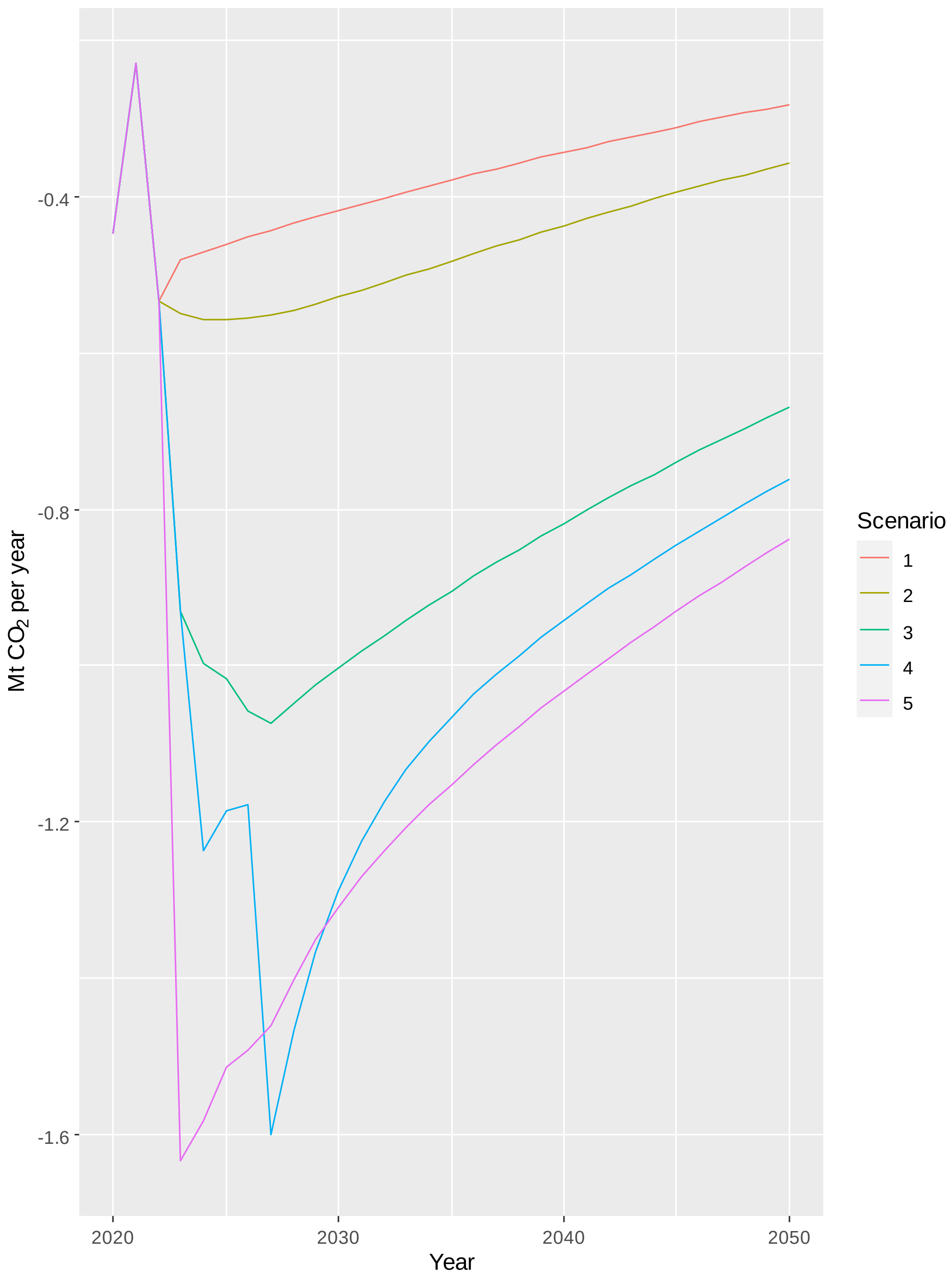

Figure 2: Carbon sink as a sum of all products in Mt CO_2 per year for the five scenarios in the years 2020–2050.The x-axis shows the year, and the y-axis shows the carbon sink/source. Negative numbers indicate carbon sink and positive numbers indicate a carbon source.

The annual changes in carbon storage in sawnwood, panels, paper, and textiles for the five scenarios for the years 2020 to 2050 were calculated. Figure 3 shows the changes in carbon sink for sawnwood, panels, paper, and textiles for the five different scenarios (numbers in bold) during the years. For each scenario, the red line indicates sawnwood products, the green line indicates panels and panelboards (i.e., MDF, particle boards and fiberboards), the blue line indicates paper and paper products (here BCTMP is also included), and the grey line indicated textiles (manmade cellulosic fibers).

Using wood for producing HWPs with long lifespans, like sawnwood products, is important as then the oxidisation of the carbon in harvested wood can be postponed considerably. However, the HWP carbon pools constantly emit carbon from HWPs that are reaching their lifetime and are decaying. A continuous increase in production is needed to not decrease the carbon sink over time. This is illustrated especially well for sawnwood in scenarios 1 and 2. Even if the productions were the same for all years, there was a clear decrease in sink over time. In fact, for scenario 1 in 2022, 74% of the production of sawnwood coming to the HWP carbon pool was used to compensate for carbon released from former sawnwood products. This proportion increased to 87% in 2050. For all scenarios, the carbon pool for paper products was emitting more carbon than sequestering in 2022 and the inflow was not able to compensate for carbon released. Hence, the pool was neutral after some years.

When comparing the scenarios, the confirmed plans for increased production capacities for sawnwood in scenario 3, are very important from a carbon storage perspective. In 2027, carbon storage in sawnwood is increased by 1.03 Mt CO_2 in scenario 3. The increased production capacity for panels in scenario 4 will first increase the sink to 0.20 Mt CO_2 in 2027, but this sink will be reduced to 0.11 Mt CO_2 in 2050.

Changes in production affects carbon storage. Using sawnwood chips and sawdust particularly to panel products instead of to biofuels and pellets will lengthen the storage time of carbon, and a carbon sink can be created. In scenario 5, net exports of wood were used for domestic production of sawnwood, panels and textiles, resulting in the wood being included in the domestic carbon storage. Paper and textiles did not provide any long-lasting sink. Due to the fast oxidation, the negative values shown in Figure 3 are quickly returned to zero within a few years.

For scenario 4, an increase in production to include biofuels and plastic pellets did not increase the carbon storage. Using sawmill chips and sawdust for panels, paper, and textiles, instead of biofuels and pellets will store carbon for a longer time and create a carbon sink.

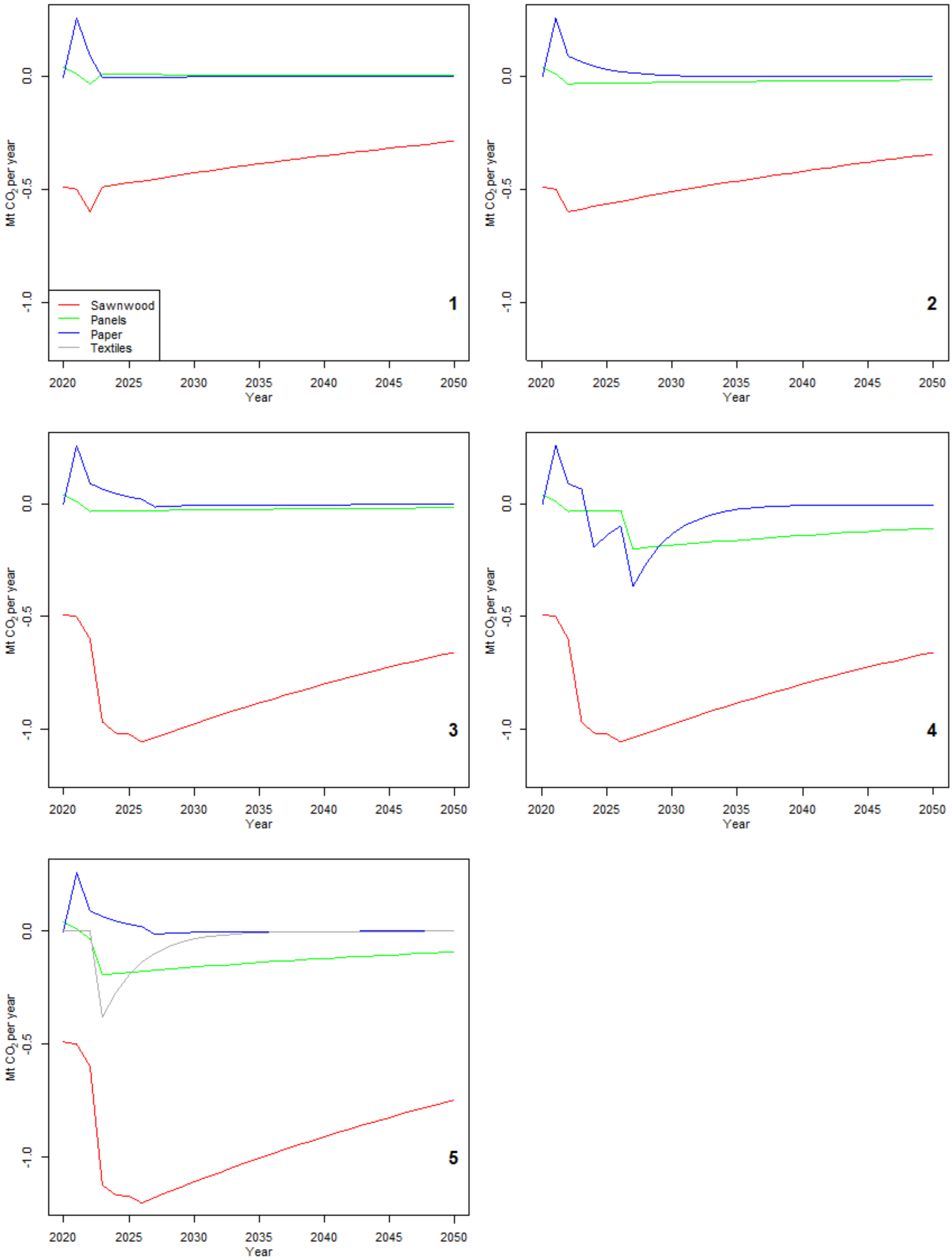

Figure 3: Change in carbon sink for sawnwood, panels, paper, and textiles for the five different scenarios (numbers in bold) in years 2020–2050. Negative numbers on the y-axis indicate a carbon sink and positive numbers indicate a carbon source. The red line indicates sawnwood products, green line indicates panels and panelboards (i.e., MDF, particle board and fiberboard), blue line indicates paper and paper products (here BCTMP is also included), grey line indicated textiles (manmade cellulosic fibers).

4.2. Carbon substitution

The total effects of using HWPs for substituting other, more carbon intensive materials are presented in Figure 4 where 5000 state-of-natures were calculated to assess the uncertainty of the parameters.

The results from the Monte Carlo simulations are also presented as cumulative distributions (Figure 5). In both cases, the substitution effects are calculated per cubic meter of industrial roundwood harvested in the scenario. The cumulative distributions show that 50% of all states-of-natures calculated for scenario 1 had a substitution benefit corresponding to at least 0.79 t CO_2/m^3, i.e., median value. In total 50% of all states-of-natures had a substitution benefit of more than 0.79 t CO_2/m^3, 0.82 t CO_2/m^3, 0.76 t CO_2/m^3, and 0.85 t CO_2/m^3 for scenarios 2 to 5, respectively.

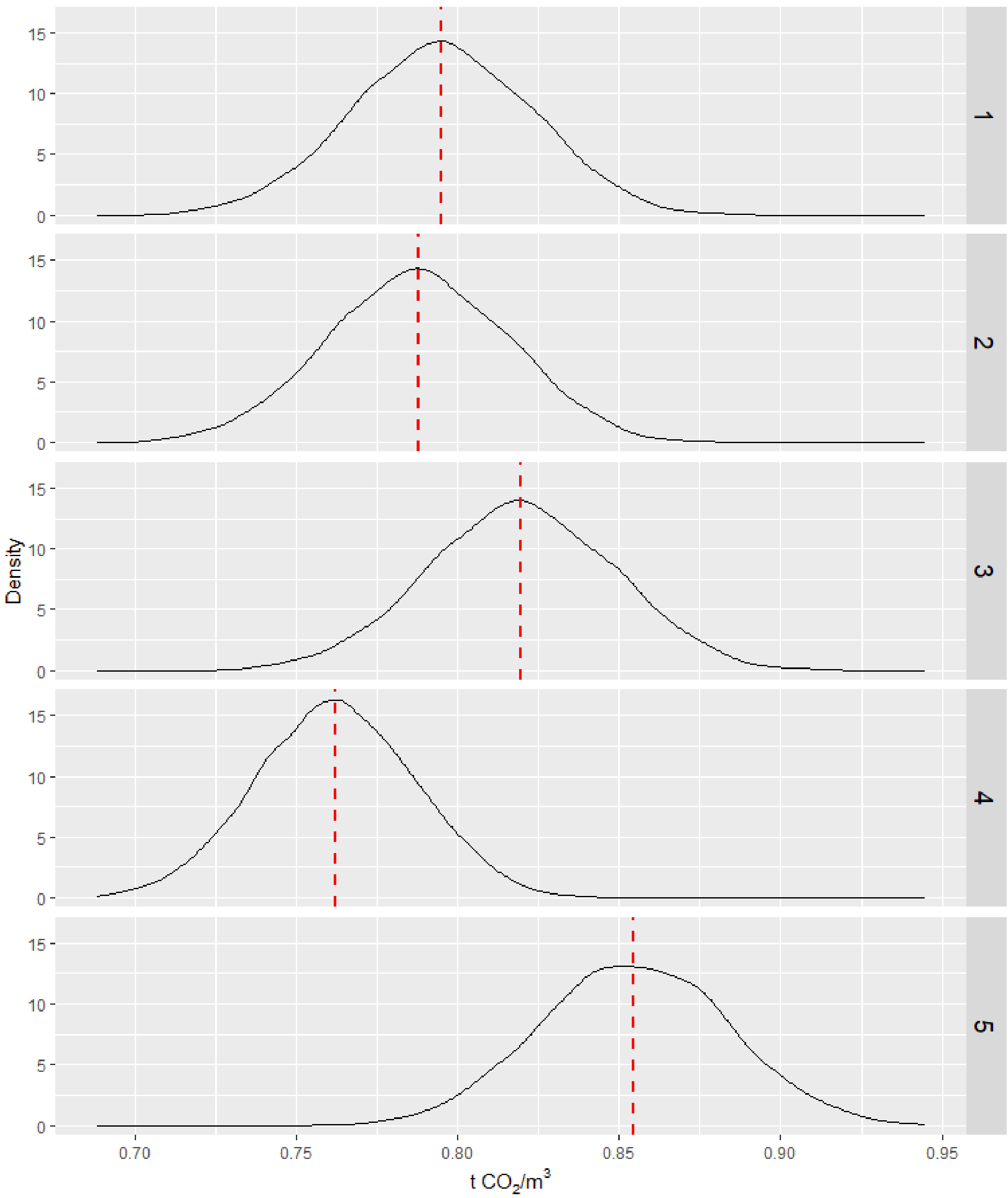

Figure 4: Density plots with mean of total substitution benefit in t CO_2/m^3 for the five different scenarios. The red line illustrates the mean substitution in t CO_2/m^3, and the black line is the probable density of the datapoints observed for the 5000 state-of-natures calculated to access the uncertainty of the parameters.

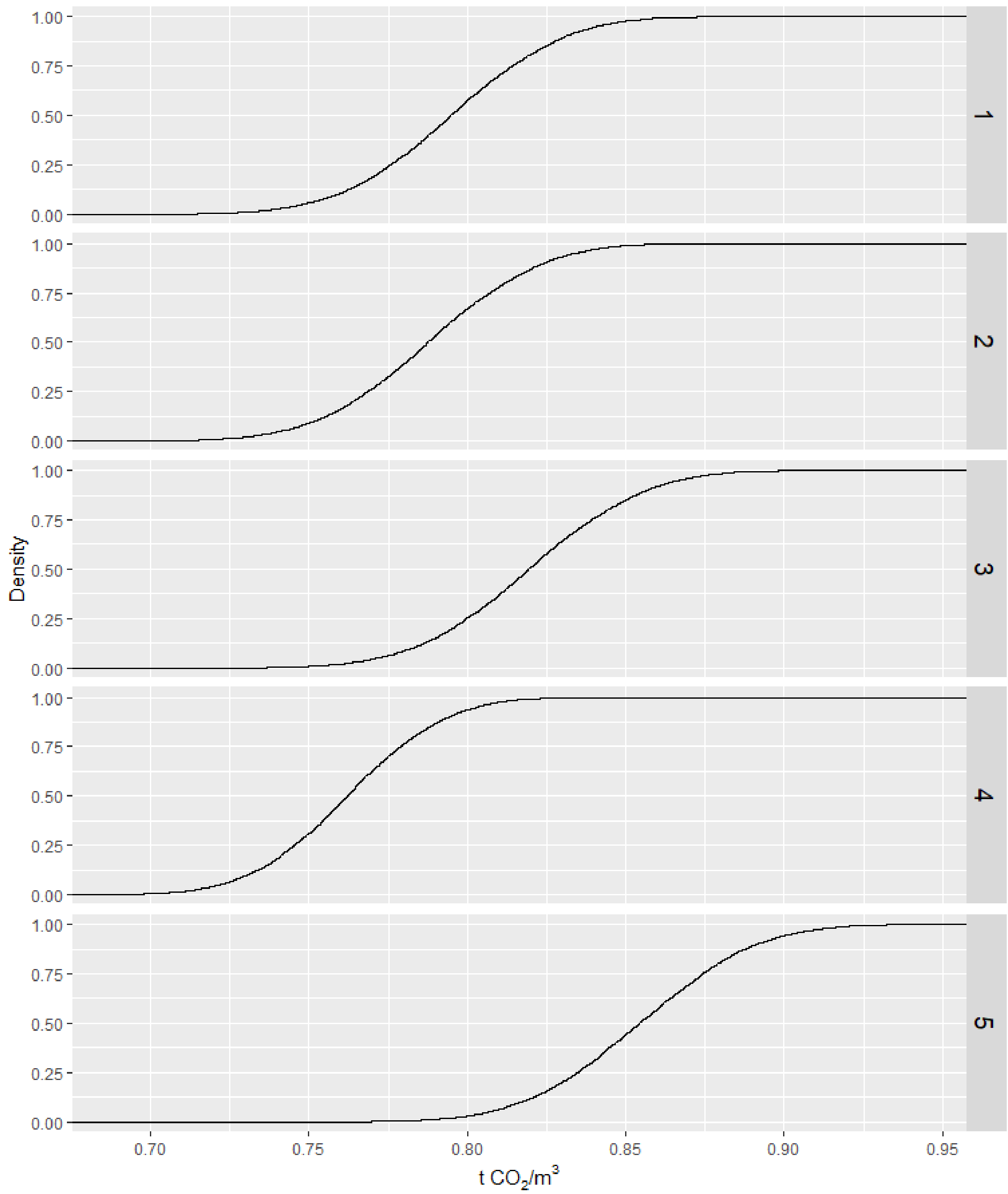

Figure 5: Cumulative distribution for scenarios 1 to 5. The black line is the cumulative probable density of the datapoints observed for the 5000 state-of-natures calculated to access the uncertainty of the parameters.

The mean substitution factor was largest for scenario 5, with a mean carbon substitution factor of 0.85 t CO_2/m^3 (Table 5). For scenarios 1 to 4, the mean substitution factors were 0.80, 0.79, 0.82, and 0.76 t CO_2/m^3, respectively. Thus, scenario 5 stores the most carbon per m^3 through carbon substitution and scenario 4 the least. The standard deviations for the results obtained from the Monte Carlo simulations were quite similar. For the scenarios 1 to 5 the standard deviations were 0.028, 0.028, 0.029, 0.025, and 0.029 t CO_2/m^3, respectively. The Welch two-sample t-test showed that the differences were all statistically significant ($p<0.01$) meaning that all mean substitution factors were significantly different between all the pairs of scenarios. As shown in Figure 4, the distribution curves have quite similar shapes. This indicates that the uncertainty was quite similar for the scenarios.

Table 5: Industrial roundwood harvest, substitution benefits from production made of harvested wood domestically and abroad, and total and mean substitution benefits in scenarios 1–5.

Scenario	1	2	3	4	5
Harvest, Mm^3	10.812	11.452	11.452	13.0168	11.452
Harvest in Mt C[a]	2.43	2.58	2.58	2.93	2.58
Substitution from domestic prod., Mt CO_2	6.52	6.74	7.72	9.67	9.79
Substitution from products abroad, Mt CO_2 [b]	2.08	2.28	1.66	0.25	0
Total substitution, Mt CO_2	8.60	9.02	9.39	9.92	9.79
Mean substitution benefit, t $C0_2/m^3$	0.80	0.79	0.82	0.76	0.85
Mean substitution benefit, t C/ tC[c]	0.96	0.95	0.99	0.92	1.04

[a] Harvest multiplied by 0.225 tC/m^3, which is estimated to be carbon content for coniferous roundwood per m^3 (IPCC, 2006a).
[b] Sawnwood and paper products assumed produced from wood (net) exported from Norway.
[c] Substitution benefit per tC of industrial roundwood harvested in the scenario.

When comparing the ratio of substitution from domestic production and exported products the results showed that scenario 2 had the largest substitution from exported products compared to any other scenario, followed by scenario 1.

When comparing the scenarios 1 and 2 (Figure 4), scenario 1 had a larger mean substitution benefit. Even if scenario 1 has a smaller total substitution benefit of Mt CO_2, the smaller harvest resulted in the mean substitution in t CO_2/m^3 becoming a bit larger (Table 5). Scenario 3 had a larger mean substitution compared to scenario 2. The reason for this is due to the increased production of sawnwood products, which has a large substitution factor in the production and use stage. Scenario 4 has the smallest mean substitution benefit out of all scenarios. Despite the increased production, this scenario had a large share of biofuels and BCTMP, which both have relatively small substitution factors. However, there is some uncertainty regarding the end products manufactured from BCTMP. The CSF was estimated based on the average CSFs of the two product categories: printing and writing paper, and paper and paperboard mostly used for wrapping and packaging. Scenario 5 demonstrated the largest mean substitution benefit primarily because it utilized the wood production that was assumed to be net exported, for domestic production of sawnwood, panels, and wood-based textile fibers, instead of being exported for sawnwood and paper production abroad. Panels and wood-based textile fibers have larger substitution factors than paper products, thereby resulting in a more substantial benefit.

The magnitude of the substitution benefits of HWP production can also be compared to the carbon stored in the industrial roundwood used to attain that production (Table 5). Only in scenario 5 was the substitution benefit larger than the carbon stored in wood used as an input for the production.

The substitution benefit at the production and use stage was greater than the substitution benefit at the end-of-life stage for the product portfolio in each scenario (Figure 6). The reason could partly be due to the amount of dissolving pulp, as well as the pellets and biofuels mainly in scenarios 3 and 4, which did not have any substitution factor for the end-of-life stage. In scenario 4, the substitution benefit for the end-of-life stage was considerably smaller than the production and use stage, with the mean values of 0.46 t CO_2/m^3 and 0.30 t CO_2/m^3 for the production and use and end-of-life stage, respectively. The reason could be mostly due to the share of biofuels and pellets which only has substitution factors for the production and use stage, since they were burned as heat or fuel. Scenario 3 had a larger mean substitution benefit for the production and use stage compared to scenario 2, with the mean values of 0.45 t CO_2/m^3 and 0.47 t CO_2/m^3 for scenarios 2 and 3, respectively, despite the production being the same. The reason for this was the larger amount of sawnwood products in scenario 3 compared to scenario 2. Scenario 5 had a greater share of sawnwood products, panels, and textiles, compared to scenario 3, which all have large substitution factors making the mean substitution benefits for both production and use and end-of-life stages greater.

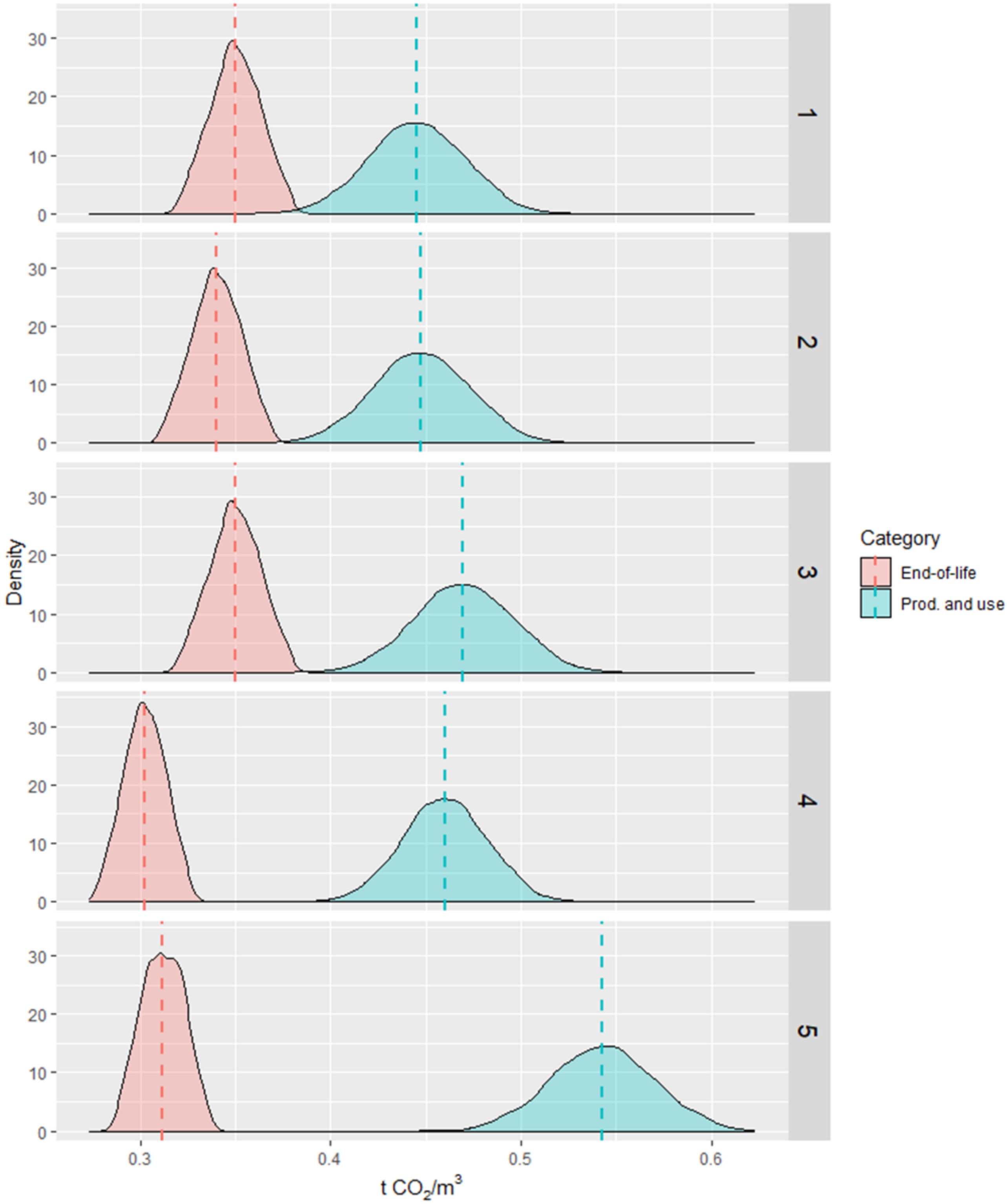

Figure 6: Density plots with means of substitution benefits in t CO_2/m^3 for the stages production and use, and end-of-life for the HWPs in the five different scenarios. The dashed lines illustrate the mean substitution in t CO_2/m^3, and the black lines are the probable density of the datapoints observed for the 5000 state-of-natures calculated to access the uncertainty of the parameters.

5. Discussion

Norway has a forest policy which aims to increase forest carbon stocks (Norwegian Ministry of Climate and Environment, 2020). However, the forest capacity as a carbon sink might have reached its peak and the annual increment is likely to decrease over time, due to the increasing amount of old forest. According to the FRLs, the harvests in forested land are expected to increase, as well as measures to increase the forests capacity to act as a carbon sink. Despite the increased harvest levels, the forest is anticipated to experience growth in standing volume and remain a significant carbon sink in the coming century (Norwegian Ministry of Climate and Environment, 2020).

In this study five different scenarios were defined. The scenarios differed in their wood use, where scenario 1 had the smallest and scenario 4 had the largest use. Scenario 4 had an increased harvest of 1.6 Mm^3, which is 14% above the harvest level for 2021. Nonetheless, all scenarios had harvest volumes that were below those set in the FRLs for the period 2021–2025. According to the Norwegian Ministry of Climate and Environment (2020), such levels are not anticipated to have adverse effects on the forest ecosystem or its carbon sequestration capabilities.

In the initial years of all the considered scenarios, the carbon pool associated with the paper products acted as a carbon source. This was attributed to the decay of prior paper products present in the pool, coupled with the declining paper production levels observed in Norway over the past few years (Figure 3). The pulpwood previously used for that domestic paper production is currently exported and is therefore not added to the carbon storage in the Norwegian GHG reporting to UNFCCC according to the rules from IPCC (Alfredsen et al., 2022; IPCC, 2013). The decrease in consumption and paper production is partly due to digital magazines, online publications and internet (Bøhmer, 2022). If the exported pulpwood converted to pulp and panel products abroad had been included in the Norwegian carbon storage calculations, then the carbon emissions from the paper product stock would have been reduced. However, it must be noted that in order to maintain the sink in any longer period, production must increase. Particularly, for the products with short-life time the sink is not very persistent.

When comparing the scenarios, the results showed that scenario 5 was more proficient at replacing carbon-intensive materials with less carbon-intensive alternatives, as well as for storing carbon. Scenario 5 demonstrated 25–36% larger carbon sink than scenario 3, depending on the year being considered. Additionally, the mean substitution for scenario 5 was 0.03 t $C02/m^3$ larger than scenario 3, which was the second-best option for substitution. However, the confirmed production in scenario 3 also increased the carbon sink substantially compared to scenarios 1 and 2 of previous production and scenario 4 including investments under consideration. The potential of HWPs acting as an increased carbon sink depends on the lifetime of products being produced in the scenarios, as it is reflected in the results.

The Norwegian government has set targets to increase the use of biofuels from 2022 and gradually increase this up to 40% in 2030 (Norwegian Ministry of Climate and Environment, 2020; Norwegian Ministry of Climate and Environment, 2021). As shown in this study, biofuels have relatively low CSFs and do not provide any benefits for carbon storage. This indicates that, for the purpose of mitigating climate change, it would be more advantageous to manufacture products with increased CSFs and longer lifetimes, rather than utilizing biomass for biofuel production.

The results showed that Norway has a great potential to increase both the storage and substitution benefits even further. Black pellets are made from logging residues, and in scenario 4 the added particleboard was made of return wood and the paperboard was made of recycled paper, which did not influence the harvest levels (Kløvstad, 2022; Prosess21, 2020; Venn, 2022). Creating products as biofuels, pellets, particleboard, and paper products of wood materials that do not increase the harvest level can increase the substitution benefits and promote climate mitigation. Unfortunately, removing logging residues in a larger scale might have negative impacts on biodiversity and soil nutrients (Ranius et al., 2018).

Several uncertainties are involved when calculating the substitution benefits for different product portfolios. The substitution factors can vary by regions and method of production in both the substituted and the substituting product. Furthermore, assumptions are needed to predict some substitution factors as they are not readily available for all products. They may also be change due to the changes in energy production due to shift from fossil energy to renewable energy (Hurmekoski et al., 2020). Thus, the substitution factors are dynamic as they can change over time (Myllyviita et al., 2021).

The ideal method for determining carbon emission related to a product would involve assessing its entire lifecycle, from production and use to end-of-life. Nonetheless, it is essential to establish clear system boundaries. For example, for HWPs, it could be possible to consider the carbon sequestration effects that would have occurred in the forest if the tree was not harvested, and the product not produced when determining lifetime emissions. However, incorporating such factors into substitution coefficients could lead to double counting of forest-related emissions and blur overall carbon accounting (Kallio et al., 2023). Moreover, the climate impact of forest land use depends heavily on factors such as management practices, forest age, type, and location, as well as the timeframe under consideration. Additional elements such as changes in forest carbon sequestration can be brought into the analysis by employing a forest model that accounts for these variables, as demonstrated in studies such as Braun et al. (2016), Kallio et al. (2013), and Werner et al. (2010).

Because substitution benefits are related to emissions that did not occur, they can only be made visible by calculating them. More detailed calculations are therefore needed, and this information could be beneficial when creating strategies on how the forest and forest sector better can contribute to climate change mitigation. If this was established, governmental strategies would most likely not support increased production of biofuels produced from pulpwood. To contribute to the goal of limiting global warming to 1.5 degrees Celsius as stipulated in the Paris agreement, a climate-smart forestry is needed. The climate-smart forestry should involve utilizing available raw materials to produce products in demand that offer the greatest substitution benefits, preferably coupled with longer lifetimes.

6. Conclusions

Five scenarios were created to calculate the storage and substitution benefits of current, confirmed, potential and favorable production portfolios of HWPs in Norway. Scenario 5, where the exported wood in scenario 3 was used for domestic production of HWPs with increased carbon substitution factors and longer life spans, had the greatest storage and substitution per cubic meter of wood used. Scenario 4 where non-confirmed capacity investment plans aired by the potential investors were added to the production of HWPs in 2021, had the largest share of biofuels and pellets, and showed the smallest substitution per cubic meter wood used. The carbon sink in scenario 3, where recently established or confirmed production capacity investments in Norway were added to the production of HWPs in 2021, showed a substantial increase compared to the values obtained from the previous production in scenarios 1 and 2, and scenario 4.

The range of carbon sink from 0.42 Mt $C0_2$ to 1.31 Mt $C0_2$ for the different scenarios in 2030 were in line with numbers reported by the NIR and FRLs for 2021–2025 (Norwegian Ministry of Climate and Environment, 2020; The Norwegian Environment Agency et al., 2022). The sink decreased over time in all scenarios because the forest industry production was kept constant after some initial increases. The mean substitution benefits per year ranged from 8.60 Mt $C0_2$ to 9.79 Mt $C0_2$ across the scenarios. Thus, the substitution benefits are considerably larger than carbon sink effect of HWPs. Substitution benefits therefore add an important positive impact on the emissions reductions provided by the forests.

The substitution benefits are indirectly included in the GHG reporting to the UNFCCC due to the avoided emissions as the result of increased use of HWPs. Substitution benefits should be calculated and considered, however, to illustrate how much emissions are avoided by substitution. This information is important for mitigating climate change more effectively. By accounting for the substitution benefits, policymakers can create more effective regulations and policies in the forest and forest sector to optimize global climate change mitigation efforts. It is important to note that a product might have varying CSFs due to differences in applications and assumptions. As shown in this study these uncertainties should be considered when calculating the substitution benefits of HWPs. To contribute to the goal of limiting global warming, a climate-smart forestry, utilizing available raw materials to produce products in demand that offer the greatest substitution benefits, preferably coupled with longer lifetimes, should further be implemented.

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Appendix

Table A1: Confirmed capacity of forest industries since 2022

Company	Product produced	Input raw material (m^3)	Output product[a]	Unit	Starting year	Source[b]
Bergende Holm AS	Sawnwood	350 000	175 000	m^3	2022	1
AT Skog -Telemarksbruket	Sawnwood	55 000	27 500	m^3	2022	1
InnTre Kjeldstad AS	Sawnwood	440 000	220 000	m^3	2022	1, 2
Moelven (Norway)	Sawnwood	72 000	36 000	m^3	2022	1
Gausdal Treindustrier	Sawnwood	25 000	12 500	m^3	2023	1
Gran Treindustrier	Sawnwood	55 000	27 500	m^3	2023	1
Fåvang Treindustrier	Sawnwood	20 000	10 000	m^3	2023	1
Begna bruk and Ringalm	Sawnwood	125 000	62 500	m^3	mid 2023	1
Hasle sagbruk	Sawnwood	350 000	63 000	m^3	2025	3
Norske Skog - Demo plant	Plastic pellets (CEBICO)		300	tons	2022	4
Glommen technology	White pellets	200 000	55 000	tons	2022	5
Arbaflame	Black pellets		70 000	tons	2022	6
Vajda-papir	Toilet/kitchen paper		25 000	tons	2026	6

[a] Calculated based on conversion factors (see appendix, Table 3)

[b] 1. Bjørndal (2022a), 2. InnTre Kjeldstad AS (2022), 3. Venn (2022b), 4. Venn (2022d), 5. Glommen Technology AS (2021), 6.Arbaflame (2022), 7. Venn (2022c)

Table A2: Potential production capacity

Company	Product produced	Input raw material (m^3)	Unit	Output product[a]	Unit	Starting year	Source[b]
Norwegian Fiberboard	MDF (boards)	300 000	m^3	168 000	m^3	2026	1
Forestia[c]	Particleboard	100 000	tons[d]	100 000	m^3	2026	2
Ranheim Paper and Board[c]	Paperboard			50 000	tons	2026	3
Treklyngen tremasse-produksjon	BCTMP	500 000	m^3	200 000	tons	2023	4
Norske Skog Saugbruk	BCTMP	500 000	m^3	175 000	tons	2026	5
Norske Skog Full scale facility	Plastic pellets (CEBICO)	60 000	m^3	50 000	tons	2023	6, 7
Silva Green Fuel	Bio-oil	1 000 000	m^3	100 000	m^3	2026	8, 9
Shell / Bergene Holm	Bio-oil	700 000	m^3	120 000	m^3	2026	10, 11, 12
St1 Follum	Bioethanol	500 000	m^3	50 000	m^3	2026	12

[a] Calculated based on conversion factors (see appendix, Table 3)
[b] 1. Norwegian Fiberboard AS (2022), 2. Kløvstad (2022), 3. Venn (2022c), 4. Bjørndal (2022b), 5. Venn (2022e), 6. Venn (2022a), 7. Venn (2022d), 8. Silva Green Fuel (2023), 9. Kippenes (2022), 10. Biozin (2021), 11. Biozin (2023), 12. Prosess21 (2020).
[c] Made by 100% return wood
[d] Devided by 0.665 t to be converted to m^3

Table A3: Conversion factors for converting raw material into output product

HWPs	Conversion factors[a]	Unit
Sawnwood	2.00	m^3 wood/m^3 product
Fiberboard, medium/high (MDF/HDF)	1.6	m^3 wood/m^3 product
Particle board	1.5	m^3 wood/m^3 product
Wood-based ethanol	8.6	m^3 wood/m^3 product
Paper	2.6	m^3 wood/t product
Pulp for textile fibers[b]	6	m^3 wood/t product

[a] FAO et al. (2020)
[b] Assumed by author

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