On Carbon Substitution and Storage Factors for Harvested Wood Products in the Context of Climate Change Mitigation in the Norwegian Forest Sector

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Abstract – Harvested wood products (HWP) can play an important role in climate-smart bioeconomic transformation. They contribute to climate change mitigation through two main mechanisms: carbon storage and substitution. Norway has ambitions to strengthen the contribution of its forest sector in climate change mitigation. Ideally, the future production and use of HWPs would increasingly shift towards products with high carbon storage and substitution benefits. We collected data from the literature and, when necessary, supplemented it with our own calculations, on carbon storage and substitution factors of HWPs that seemed relevant in evaluating the climate change mitigation potential in the context of the Norwegian forest sector. There are many uncertainties in the parameters. We identified and examined in more detail some uses of wood for industrial products that offer clear substitution benefits and, in some cases, long-term carbon storage. Wood-based construction materials, textile fibres, and insulation materials are examples of such products that could have high potential in the bioeconomy transformation in Norway.

Keywords – Carbon displacement factor; forest industry; forest products; mean lifetime; wood-based insulation materials; wood-based textiles.

1. INTRODUCTION

Harvested wood products (HWPs) contribute to climate change mitigation via two main mechanisms: carbon storage and substitution. Concerning storage, HWPs form a carbon reservoir (pool) in which carbon sequestered into trees resides after harvests. In some HWPs, e.g., fuelwood, carbon remains only for a while before being oxidized. In some uses, carbon is stored for years, decades, or even centuries. The net increase in the HWP carbon pool provides a carbon sink. Substitution benefits are obtained if the use of an HWP in an end-use, e.g., window frame, leads to lower greenhouse gas (GHG) emissions during a life cycle than products made of other materials serving the same function [1], [2]. Not all uses of HWPs provide substitution benefits, but, in some cases, the benefits can be substantial. Sometimes, substitution benefits take a long time to realize. For instance, wood-based bioenergy does not provide immediate benefits compared to fossil fuels [3]–[5]. However, unlike emissions from the use of fossil fuels, carbon released from bioenergy will be tied back to new growing biomass over time. Sometimes, energy biomass comes in form of a process or end-of-life
cycle waste that would oxidize in any case and possibly even produce methane emissions [3], [6].

Norway aims to strengthen the role that its forest sector plays in climate change mitigation and bioeconomic transformation. Analyses of the overall climate change mitigation potential of Norwegian forests, the forest sector, and HWPs produced require data. To facilitate such analyses and consequent decision and policy making, we examine the carbon storage and substitution coefficients of HWPs that we considered to be currently relevant or promising for the future transition towards a circular bioeconomy in Norway. Based on the data, we identified three product groups that could be interesting from the point of view of the climate-smart bioeconomic transformation in the Norwegian forest sector: sawnwood, wood-based textiles, and wood-based insulation materials. These products were further examined and discussed in detail. Wood-based energy products were excluded from the study, as they were recently addressed for Norway in [7]. Our analysis also explores the potential range of the substitution benefits of the forest industry production and lifetime of roundwood harvested currently in Norway. These estimates have not been provided for Norway earlier. Nevertheless, our main objective is to provide a basis for assessing the climate benefits for alternatives pathways for bioeconomy transition in Norway. Such assessments have been conducted for Finland [8], [9] and Switzerland [10].

The remainder of this paper is organized as follows. Section 2 presents measures for addressing the climate change mitigation potential of HWPs in the literature and, specifically, in carbon storage (Section 2.1) and substitution (Section 2.2) contexts. Section 3 provides carbon storage coefficients and substitution factors based on the literature and includes the more detailed discussion for product groups selected for further examination. Sections 4 and 5 present general discussion and conclusions.

2. METHODOLOGY

For the data on carbon storage and substitution parameters, we primarily relied on existing literature and earlier studies that have elaborated plausible values for the parameters. If deemed necessary and feasible, we supplemented the data with our own calculations. Based on the results, we chose three product groups for a more detailed discussion. To shed light on the carbon storage and substitution parameters and their use, we discuss the methodologies behind these parameters in this section. We also provide data that can be used to convert wood products into carbon.

2.1. Measuring Carbon Storage and Substitution

There are various means to keep track of and calculate the carbon storage within the HWP carbon pools and to calculate carbon substitution factors. These methods and approaches are related to the context and purpose of their use. In the countries’ reporting of their GHG inventories to the United Nations Framework Convention on Climate Change (UNFCC), all annual net emissions or emissions savings are converted to equivalents of the most well-known and common greenhouse gases, carbon dioxide (CO₂). This simplifies the assessment of the radiative forcing of different GHGs (e.g., methane and water vapor) and their mixtures. The different emissions are converted to CO₂-equivalents (CO₂-eq) by multiplying them with their respective global warming potentials (GWP) for a given time horizon [11]. The default timeframe of 100 years, also applied to the parameters in this study, was adopted during the UNFCC and used in the Kyoto protocol [12]. However, there is no scientific basis for this choice which has a large impact on GWPs [13].
2.1.1. Carbon Storage

When the amount of carbon in a pool other than the atmosphere (e.g., forest land, HWP) diminishes from one year to another, the pool is considered a carbon source. Conversely, the pool is a sink. To calculate the sink or source of HWPs, the carbon entering and leaving the pool must be measured. The carbon entering the stock is quantified by applying conversion rates that give the mass of carbon stored in an HWP to the relevant HWP activity data, e.g., data on production. The decay of the carbon in the HWP pools is often modelled using the product half-life ($HL$) which corresponds to the number of years it takes to lose half of the material in the pool [14].

The Intergovernmental Panel on Climate Change (IPCC) lists four approaches to calculate the carbon stock of HWPs [15]. The stock-change and production approaches are based on carbon stock changes within a defined pool of HWP, whereas atmospheric-flow, and simple-decay, are based on CO$_2$-fluxes to and from the atmosphere from HWP [15]. Simple-decay and production approaches consider where HWPs are produced, irrespective of where they are consumed [15]. The choice of approaches depends on the data availability and context of use. One might be interested in knowing how much carbon accumulates in the HWP pools in Norway owing to Norwegian consumption. One could also be interested in determining the amount of carbon that leaves the Norwegian forest pool but remains in the HWP pools worldwide.

To provide an example of the calculation of HWP carbon pools and to shed light on the use of the parameters in Section 3, let us describe the main elements of the production approach that is used to calculate the changes in HWP pools in Norway for UNFCC reporting [16]. The approach follows the default Tier 2 method of the IPCC [17] where the carbon pools are tracked for three categories: sawnwood, wood-based panels, and paper and paperboard. Only production based on domestic wood harvest is included. The volumes of HWPs are converted to carbon using default conversion factors, $cf$ (Table 1). The carbon stock and its change in a particular HWP category in year $i$ are calculated using Eqs. (1) and (2), respectively [14], [17].

\[
C(i+1) = e^{-k} C(i) + \left[ \frac{1 - e^{-k}}{k} \right] \cdot \text{inflow}(i),
\]

\[
\Delta C(i) = C(i+1) - C(i),
\]

where
- $C(i)$ Carbon stock (kt C) at the beginning of year $i$;
- $k$ Rate at which carbon is removed from the pool (first order decay rate);
- Inflow($i$) Flow of carbon into the pool;
- $\Delta C(i)$ Carbon stock change (kt C) in the pool in year $i$.

The decay rate $k$ is defined as $k = \ln(2)/HL$ where $HL$ is the half-life of the HWP pool (years). Inflow($i$) is calculated using Eq. (3) [14]:

\[
\text{Inflow}(i) = HWP_p(i) \cdot f_R(i) \cdot cf,
\]

where
- $f_R(i) = \begin{cases} f_{IRW}(i) & \text{for HWP categories sawnwood and wood-based panels} \\ (f_{IRW}(i) \cdot (1-q) \cdot f_{PUP}(i)) + q \cdot f_{RecP}(i) & \text{for HWP category paper and paperboard} \end{cases}$
The shares of woody feedstock in the total production volumes are calculated by subcategories, $f_{IRW}$ for ‘industrial roundwood’, $f_{PUPL}$ for ‘wood pulp’, and $f_{RecP}$ for ‘recovered paper’, and recovered paper utilization rate $q$. The initial carbon stock $C(t_0)$ for an HWP category is based on the average inflow of carbon to the pool during the first five years for which statistical data are available, starting from 1961 in the case of Norway.

Sometimes, the mean lifetimes (ML) of HWPs are reported instead of HLs. In the first-order decay processes, ML is the time $t$ defined by $t = 1/k$. Thus, half-life can be calculated from $HL = \ln(2) \cdot ML$. In addition to exponential decay rate model, other approaches used for modelling the oxidation rate of HWPs include, e.g., the use gamma distribution [18] or its special case, Chi square distribution [19]. Iordan et al. [19] argue that exponential decay rate may be an over-simplification of the real decay rate, whereas gamma distribution would be more realistic but would require a year of expected 95 % oxidation as additional parameter.

### 2.1.2. Carbon Substitution

The climate change mitigation impact of substituting wood products with non-wood products is quantified by comparing the life cycle GHG emissions between products. Different volumes of materials may be needed to accomplish the same functional purpose over time. Thus, for these comparisons to be consistent, the end products or materials must be functionally equivalent [2].

Non-wood products may also contain wood. Therefore, a comparison of GHG emissions between wood and non-wood products is often expressed relative to the difference in the amount of wood used in the products. These carbon substitution factors (CSFs), often also called carbon displacement factors, are calculated as [1]:

$$CSF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \quad (4)$$

where

- $GHG_{non-wood}$: GHG emissions;
- $GHG_{wood}$: GHG emissions;
- $WU_{non-wood}$: Amounts of wood used, applied to functionally equivalent product volumes;
- $WU_{wood}$: Amounts of wood used, applied to functionally equivalent product volumes.

The emissions are expressed in tonnes of CO$_2$-eq or C, whereas wood use can be measured in e.g., cubic meters of wood or the amount of carbon stored in wood. The fact that the $WU$ used in the calculations may refer to the wood, to carbon remaining in the unit of product, or to wood used for producing the unit of product complicates the comparison of the substitution coefficients between the studies. The GWPs of the compared products can be used as figures for the GHGs in Eq. (4) given that they refer to functionally equivalent product volumes.

Ideally, all GHG emissions during the life cycle of a product are considered to define the CSFs. However, system boundaries must be clearly defined. For instance, for forest products, the effects of carbon that would have been sequestered in the forest if an HWP had not been produced could also be considered. Nevertheless, changes in carbon in pools of managed forests and HWPs are measured and reported in the carbon accounting of Land Use, Land Use Change and Forestry. Encompassing these into the substitution coefficient would complicate
the evaluation of the overall climate impacts of the forests and HPWs due to double counting of forest emissions. Changes in forest carbon storage can be brought into the analysis as an additional element by using a forest model that can consistently account for the above issues, such as in [20]–[23].

2.2. Converting the Volumes of HPWs to Units of Carbon

The carbon storage parameters and carbon displacement factors of the HPWs appear in various units. Table 1 shows the conversion of common forest products to their respective carbon equivalents. The data are subject to regional variation, depending on the wood species used. Table 2 shows the structure of the forest industry production in Norway and provides an overview of how the carbon in harvested roundwood divides between the HPWs produced domestically, roundwood exports, and other uses (mainly energy production within forest industries).

### Table 1. Conversion of Common Forest Products to Carbon

<table>
<thead>
<tr>
<th>HWP</th>
<th>Output unit</th>
<th>Density (t/output unit)</th>
<th>C fraction</th>
<th>C conversion factor (t C/tonne)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundwood, Con</td>
<td>m³</td>
<td>0.45</td>
<td>0.5</td>
<td>0.225</td>
<td>[24]</td>
</tr>
<tr>
<td>Roundwood, pine</td>
<td>m³</td>
<td>0.418</td>
<td>0.5</td>
<td>0.21</td>
<td>[25] for density</td>
</tr>
<tr>
<td>Roundwood, spruce</td>
<td>m³</td>
<td>0.39</td>
<td>0.5</td>
<td>0.195</td>
<td>[25] for density</td>
</tr>
<tr>
<td>Roundwood, NCon</td>
<td>m³</td>
<td>0.48; 0.51</td>
<td>0.5</td>
<td>0.24; 0.26</td>
<td>[26], [27] (density)</td>
</tr>
<tr>
<td>Sawnwood</td>
<td>m³</td>
<td><strong>0.229</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sawnwood, Con</td>
<td>m³</td>
<td>0.45</td>
<td>0.5</td>
<td>0.225</td>
<td>[17]</td>
</tr>
<tr>
<td>Sawnwood, NCon</td>
<td>m³</td>
<td>0.56</td>
<td>0.5</td>
<td>0.28</td>
<td>[17]</td>
</tr>
<tr>
<td>Wood-based panels (aggregate)</td>
<td>m³</td>
<td>0.595</td>
<td>0.454</td>
<td><strong>0.269</strong></td>
<td>[17], [24]</td>
</tr>
<tr>
<td>Hardboard</td>
<td>m³</td>
<td>0.788</td>
<td>0.425</td>
<td>0.335</td>
<td>[17]</td>
</tr>
<tr>
<td>Fibreboard, compressed</td>
<td>m³</td>
<td>0.739</td>
<td>0.426</td>
<td>0.315</td>
<td>[17]</td>
</tr>
<tr>
<td>Medium Density Fibreboard</td>
<td>m³</td>
<td>0.691</td>
<td>0.427</td>
<td>0.295</td>
<td>[17]</td>
</tr>
<tr>
<td>Particle board</td>
<td>m³</td>
<td>0.596</td>
<td>0.451</td>
<td>0.269</td>
<td>[17]</td>
</tr>
<tr>
<td>Plywood</td>
<td>m³</td>
<td>0.542</td>
<td>0.493</td>
<td>0.267</td>
<td>[17]</td>
</tr>
<tr>
<td>Veneer sheets</td>
<td>m³</td>
<td>0.505</td>
<td>0.5</td>
<td>0.253</td>
<td>[17]</td>
</tr>
<tr>
<td>Paper and paperboard</td>
<td>t</td>
<td>0.9</td>
<td>0.386</td>
<td><strong>0.386</strong></td>
<td>[17], [24]</td>
</tr>
<tr>
<td>MMCF</td>
<td>t</td>
<td></td>
<td></td>
<td>0.34, 0.44,</td>
<td>[28], [29]</td>
</tr>
<tr>
<td>Insulating board</td>
<td>m³</td>
<td>0.159; 0.474; 0.075</td>
<td></td>
<td>[17]</td>
<td></td>
</tr>
<tr>
<td>Blown-in insulation</td>
<td>m³</td>
<td>0.0334–0.035; 0.43–0.475; 0.0143–0.0166</td>
<td>[8] Assumed in [8]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: C – carbon, Con – coniferous, NCon – non-coniferous, MMCF – manmade cellulosic fibres (for textiles). Tree species are Norway spruce, Scots pine, and birch. Density and C conversion factor are based on dry mass over air dry volume. *Authors, based on various Environmental Product Declarations.
### Table 2. Production of Harvested Wood Products in Norway in 2020

<table>
<thead>
<tr>
<th>HWP</th>
<th>Output unit</th>
<th>Production, 1000 units</th>
<th>t C per unit</th>
<th>C in production, 1000 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial roundwood, Con</td>
<td>m³</td>
<td>10 480</td>
<td>0.225</td>
<td>2358</td>
</tr>
<tr>
<td>Industrial roundwood, NCon</td>
<td>m³</td>
<td>2031</td>
<td>0.25</td>
<td>508</td>
</tr>
<tr>
<td><strong>Total, industrial roundwood</strong></td>
<td><strong>m³</strong></td>
<td><strong>12 511</strong></td>
<td><strong>2866</strong></td>
<td></td>
</tr>
<tr>
<td>Sawnwood, Con</td>
<td>m³</td>
<td>2683</td>
<td>0.225</td>
<td>604</td>
</tr>
<tr>
<td>(Wood-based panels)</td>
<td>m³</td>
<td>458</td>
<td>0.269</td>
<td>123</td>
</tr>
<tr>
<td>Hardboard</td>
<td>m³</td>
<td>51</td>
<td>0.335</td>
<td>17</td>
</tr>
<tr>
<td>Fibreboard, compressed</td>
<td>m³</td>
<td>116</td>
<td>0.315</td>
<td>37</td>
</tr>
<tr>
<td>Particle board</td>
<td>m³</td>
<td>291</td>
<td>0.269</td>
<td>78</td>
</tr>
<tr>
<td>Pulp for papermaking</td>
<td>t</td>
<td>826</td>
<td>0.386</td>
<td>319</td>
</tr>
<tr>
<td>(Paper and paperboard)</td>
<td>t</td>
<td>933</td>
<td>0.386</td>
<td>360</td>
</tr>
<tr>
<td>Dissolving pulp</td>
<td>t</td>
<td>157*</td>
<td>0.386</td>
<td>61</td>
</tr>
<tr>
<td>Insulating board or blow-in insulation</td>
<td>t</td>
<td>38</td>
<td>0.40</td>
<td>15</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>t</td>
<td>57</td>
<td>0.44</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total, forest industry products</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>1155</strong></td>
</tr>
<tr>
<td>Net exports of industrial roundwood</td>
<td>m³</td>
<td>3223</td>
<td>0.226</td>
<td>731</td>
</tr>
</tbody>
</table>

**Abbreviations:** C – carbon, Con – coniferous, NCon – non-coniferous. Source: [30]. ‘Other agglomerates’ was assumed to be to insulation board. Carbon in the products in parentheses are not included into total carbon of industrial products. Carbon of domestic origin in paper and paperboard is included in that of pulp. Wood-based panel is an aggregate of products that are also given in more detail. *Little if any of the dissolving pulp in Norway is used for textiles [31].

### 3. Results

#### 3.1. Carbon Storage Parameters

As discussed in Section 2.1.1., tracking the carbon in an HWP pool uses knowledge of the yearly carbon inflow into the pool and the half-lives of HWPs (Eq. (1)). The HLs vary between the HWPs and their end-uses.

Table 3 shows the range of half-lives for various HWPs and end-uses we collected from literature. If a source reported the mean lifetime instead of the half-life, we converted it to HLs applying first order decay rate. Norwegian GHG reporting uses default half-lives: 35 years for sawnwood, 25 for wood panels, and 2 years for paper and paperboard [24].

Using the data in Table 2, it can be calculated that approximately 40 % of the carbon harvested as industrial roundwood in Norway in 2020 was stored for at least some time in HWPs other than energy biomass, whereas 25 % was exported. Roughly one-third of the carbon ‘vanishes’ in the industrial processes, mostly because it is used as energy. Assuming the first-order decay rate and default half-lives in Table 3 for the forest industry products other than pellets and dissolving pulp, and 0 and 2 years for the latter, the average half-life for the HWPs produced by the forest industry in Norway can be calculated to be 21.6 years. The large amount of carbon incinerated as energy in the production process drags the average HL of domestically used industrial roundwood of Norwegian origin down to 12 years. That corresponds to a mean lifetime of circa 17 years. Carbon storage in HWPs produced abroad from Norwegian roundwood should slightly increase the figure.
TABLE 3. HALF-LIVES FOR VARIOUS HWPS BASED ON LITERATURE

<table>
<thead>
<tr>
<th>HWP</th>
<th>Half-life (years)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawnwood &amp; plywood</td>
<td>27.7–52; 35</td>
<td>[17], [32]–[36]</td>
</tr>
<tr>
<td>Panels and boards</td>
<td>0.7–45; 25</td>
<td>[17], [35], [37], [38]</td>
</tr>
<tr>
<td>Paper</td>
<td>0.5–10; 2</td>
<td>[17], [33]–[35], [37]</td>
</tr>
</tbody>
</table>

Some specialized uses of HWPs

<table>
<thead>
<tr>
<th>HWP</th>
<th>Half-life (years)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaging and pallets</td>
<td>0.06–6.2</td>
<td>[32], [35], [37], [39]</td>
</tr>
<tr>
<td>Furniture</td>
<td>8.7–30</td>
<td>[32], [35], [39]</td>
</tr>
<tr>
<td>Doors and window frames</td>
<td>6.9–45.1</td>
<td>[36], [40]–[42]</td>
</tr>
<tr>
<td>Flooring</td>
<td>20.8–34.7</td>
<td>[32], [43]</td>
</tr>
<tr>
<td>Exterior cladding and terrace</td>
<td>6.9–15.9</td>
<td>[44]</td>
</tr>
<tr>
<td>Insulation</td>
<td>27.7–42*</td>
<td>[36], *</td>
</tr>
</tbody>
</table>

Note: IPCC default values in [17] are shown in *italics*. *Standard for building materials in Environmental Products Declarations.

3.2. Carbon Substitution Factors (CSFs)

A vast body of literature examines CSFs, of which [2] and [45] give recent reviews. Leskinen et al. [2] found CSFs of HWPs ranging from 0.7 to 5.1 tC/tC. The average was 1.2 tC/tC, of which 0.8 tC/tC was attributed to the production stage and the rest to the energy recovery at the end-of-life. HWPs substitute various materials in many end-uses, which contributes to this large variation.

Tables 4 and 5 show CSFs from the literature that we considered relevant in the Norwegian context, while bearing in mind that the future product portfolio of the industry may differ from that of today. When the data allowed, we converted the original figures to express the savings in GHG emissions in terms of tonnes of carbon saved per tonne of carbon in wood product (tC/tC). However, this was not possible in all cases without further assumptions.

TABLE 4. CARBON SUBSTITUTION FACTORS FOR CHEMICAL FOREST INDUSTRY PRODUCTS

<table>
<thead>
<tr>
<th>HWP by end-use</th>
<th>Non-wood product substituted</th>
<th>CSF, P</th>
<th>CSF, P+EoL</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper and paperboard</td>
<td>Not specified</td>
<td>0.00</td>
<td>0.70</td>
<td>tC/tC</td>
<td>[8], a</td>
</tr>
<tr>
<td>Graphic papers</td>
<td>Plastic, glass, and metal packaging</td>
<td>1.40</td>
<td>tC/tC</td>
<td>[8], a</td>
<td></td>
</tr>
<tr>
<td>Paperboard</td>
<td>Plastic</td>
<td>1.30</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[46]</td>
</tr>
<tr>
<td>Textiles</td>
<td>Woodfibre-based</td>
<td>–</td>
<td>2.8</td>
<td>tC/tC</td>
<td>[2], r</td>
</tr>
<tr>
<td>Viscose</td>
<td>PET, recycled PET, polyamides</td>
<td>1.24</td>
<td>1.33</td>
<td>tC/t product</td>
<td>[47]</td>
</tr>
<tr>
<td>Viscose (Austria)</td>
<td>PP (W. Europe); PET (W. Europe)</td>
<td>2.45; 3.49</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
</tr>
<tr>
<td>Viscose (Austria)</td>
<td>Cotton (US &amp; China)</td>
<td>1.81</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
</tr>
<tr>
<td>Tencel (energy from waste)</td>
<td>Cotton (US &amp; China)</td>
<td>1.59</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
</tr>
<tr>
<td>Tencel (energy from waste)</td>
<td>PP (W. Europe); PET (W. Europe)</td>
<td>2.24; 3.30</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
</tr>
<tr>
<td>Modal</td>
<td>Cotton (US &amp; China)</td>
<td>1.58</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
</tr>
</tbody>
</table>
### Table 5. Carbon Substitution Factors for Mechanical Forest Industry Products

<table>
<thead>
<tr>
<th>HWP by end-use</th>
<th>Non-wood product substituted</th>
<th>CSF, P</th>
<th>CSF, P+EoL</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP (W. Europe); PET (W. Europe)</td>
<td>2.22; 3.27</td>
<td>n.a</td>
<td>tC/tC</td>
<td>[48]</td>
<td></td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Fossil diesel</td>
<td>0.63</td>
<td>–</td>
<td>tC/tC</td>
<td>[8], a</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>Fossil ethanol</td>
<td>0.70</td>
<td>–</td>
<td>tC/tC</td>
<td>[8], a</td>
</tr>
<tr>
<td>Biobased ethylene</td>
<td>Not specified</td>
<td>1.30</td>
<td>–</td>
<td>tC/tC</td>
<td>[8], a</td>
</tr>
<tr>
<td>Lignin as adhesive</td>
<td>Phenol for adhesives</td>
<td>0.21</td>
<td>0.55</td>
<td>tC/t product</td>
<td>[47]</td>
</tr>
</tbody>
</table>

Note: P refers to the production stage (cradle to mill gate). P+EoL refers to the production stage and end-of-life. r – average based on a review; a – a study assumption. PP – polypropylene. PET – polyethylene terephthalate. W – Western.
### 3.3. More Detailed Information on Carbon Storage and Substitution for Selected Products

We will now discuss in more detail the data for product groups that we considered particularly interesting in the context of climate change mitigation in the Norwegian forest sector in the future: coniferous (softwood) sawnwood, wood-based fibres for textiles, and wood-based insulation materials. We discuss the reasons for this selection below.

**Sawnwood** has relatively long lifetime and high CSF (Tables 3 and 5). We estimated that circa 45% of the roundwood harvested in Norway is processed in sawmills to sawnwood and by-products (sawmill chips, sawdust, and bark) that can be used further for other products [30].

**Wood-based insulation materials** have only a modest share of the use of wood and the forest sector value generation in Norway. We chose to devote a more detailed discussion on this product category for the following reasons. First, they store carbon for a relatively long time and have relatively high CSF. Second, new production capacity has recently been built in this segment in Norway, and it has potential for further growth. According to Norwegian producer [53], the market share of wood in insulation materials is still rather low, below 3% in Norway and 10% in Germany. Finally, insulation materials are currently being produced from spruce sawmill chips in Norway [54]. Thus, they provide an example of a product made of wood chips that has a longer lifetime than the main alternative use of pulpwood and sawmill residuals in Norway, printing and writing papers. Demand for the latter has been declining since 2000 [30].

**Wood-based textile fibres** have a higher CSF than most other wood products. Textile consumption is an important source of global GHG emissions. The fashion industry may be responsible for up to 10% of the global emissions [55]. Most textiles consumed globally are made of oil-based materials, followed by cotton which has a much lower share [56]. Replacing these materials with wood-based fibres could relieve environmental problems from textile consumption, which makes wood-based textile fibres an interesting product for bioeconomy transformation.

#### 3.3.1. Coniferous Sawnwood

Sawnwood is used for applications with different lifetimes and CSFs (Tables 3 and 5). The climate impact of its consumption depends on the end-use division for which statistics are lacking. [57] reported that 75% of Norwegian sawnwood production is used as a building material and the rest is sold as semi-finished products. Studies in Finland [8] and Sweden
[58] assumed that most sawnwood is used in construction, while 19% go to packaging, and 3–6% go to furniture.

Storage

Sawnwood products form an important carbon pool. Norwegian sawnwood production provided a sink of 0.41 Mt CO$_2$/a, on average, in 2015–2019 [24]. The default half-life of sawnwood is 35 years, but depending on the end-use, it can be much shorter or longer (Table 3). Packaging materials have much shorter lifetimes than sawnwood used in construction. At the end of their service lives, sawnwood products are recycled, landfilled, or incinerated. The share of wood going for recycling and thereafter to incineration should increase in the future owing to new legislation restricting the amount of construction materials entering landfills [59].

Substitution

Leskinen et al. [2] found the average CSF of HWPs to be 1.3 tC/tC in structural and 1.6 tC/tC in non-structural construction, when accounting for both production and end-of-life phases. Assuming a carbon content of 0.225 tC/m$^3$ in coniferous sawnwood [12], [17], using 1 m$^3$ of sawnwood instead of other materials would save circa 1.1 or 1.3 tonnes of GHG emissions in terms of CO$_2$ in structural and non-structural construction, respectively†.

Hurmekoski et al. [8] assumed that the CSF during the production stage for sawnwood in Finland is 1.1 tC/tC when used in construction or packaging, and 0.9 tC/tC for furniture. An additional 0.7 tC/tC of emission savings could be achieved in the end-of-life stage due to energy displacement. The climate benefit of using 1 m$^3$ of sawnwood would thus be 1.3–1.5 tCO$_2$-eq.

Suter et al. [10] calculated that the CSF of sawnwood products replacing concrete and brick in construction are of the magnitude 0.10 and 0.14 tC/m$^3$ wood used, respectively. Based on [57], which suggests that 1.96 m$^3$ sawlogs are required per 1 m$^3$ of sawnwood in Norway, the range of substitution benefits for 1 m$^3$ of sawnwood used in construction would be between 0.7 and 1.0 tCO$_2$. However, the wood use coefficients in sawnwood production vary by country. [10] proposes that substitution benefits for furniture and packaging could be even higher than those obtained in construction use: using sawnwood to replace polypropylene, steel, or chromium in furniture could result in substitution benefits in the range of 0.11–0.38 tC/m$^3$ of sawlogs used. For sawnwood replacing polyethylene in packaging, the CSF was 0.38 t C/m$^3$ sawlogs used [10].

In Norway, the average sawnwood production was 2.6 Mm$^3$/a between 2015 and 2020 [30]. The CSFs discussed above regarding the main use of sawnwood, construction, suggests past substitution impacts of 2.8–3.4 Mt CO$_2$/a, 3.4–3.9 Mt CO$_2$/a, and 1.9–2.6 Mt CO$_2$/a, respectively. The figures presented in [2] were based on a review, while those from [8] and [10] reflect choices made in individual studies. This range of 1.9–3.9 Mt of CO$_2$ reduction due to sawnwood produced in Norway could be considered plausible, as it also accounts for the large uncertainty in CSFs.

† The quantity of carbon, C, can be converted to the quantity of CO$_2$ by multiplying it by 44/12.
3.3.2. Wood-based Textiles

Storage

Wood-based textiles store carbon, but there are no studies addressing the carbon stock in textiles to our knowledge. The amount of GHG released during incineration of textiles provides one measure of their carbon content. The amount of GHG released during incineration of viscose, Tencel, and Modal fibres was approximately 0.34 tC/t fibre in [28], whereas in [29] one tonne of viscose fibre made of wood was assumed to contain 0.44 t carbon. The figures are of the same magnitude than those for paper (Table 1). To calculate the carbon pools in textiles and the possible carbon sinks, information would be needed about the distribution and lifetimes of the textiles in different uses. The default half-life for pulp and paper, 2 years, was also assumed for textile fibres in [8]. The time for textiles being used has been shortening in the recent decades due to the increased availability of low-price textiles and shortened fashion cycles. An apparel item might only be used about one year [60]. The new recycling technologies [61] and legislation regarding waste landfilling and recycling [59] should help to increase the lifetimes of textile materials. In Norway, more than half of the used textiles are incinerated as mixed waste [62].

Substitution

There is a large variation in the CSFs for wood-based textile fibres calculated or used in the few studies that address them. The common factor among them is that they are relatively high. A review [2] assessed the average CSF to be 2.8 tC/tC. If one tonne of MMCF had a carbon content of 0.34 t that would correspond to 3.5 tCO$_2$-eq saved per tonne of MMCF fibre used.

Shen et al. [48] compared the cradle to factory gate GWP100 of five types of man-made cellulose fibres produced in Austria or Asia to those of cotton produced in the US and China, and polypropylene (PP) and polyethylene terephthalate (PET) produced in Western Europe. The functional unit employed was 1 tonne of fibre. Based on the GWPs reported, we calculated the CSFs between five MMCFs and non-wood fibres using Eq. (4). Viscose produced from European beech in Austria provided the highest substitution benefits among the alternatives considered, with a CSF of 0.61 tC, 0.83 tC and 1.19 tC per tonne of viscose, for cotton, PP, and PET, respectively. The CSFs of Tencel and Modal varied from 0.25 tC (Tencel against cotton) to 1.1 tC (Modal against PET) per tonne of textile fibre. Tencel figures assumed a mixture of non-integrated beech and imported eucalyptus pulp. The GWP factors in [48] were based on the actual energy used in the production stage. Thus, these GWPs and the resulting CSFs be considered rather site specific. Integrated viscose production using primarily renewable energy can be considered to represent the best available technology. Among the CSFs above, the viscose substituting polyester corresponds to GHG savings of 4.4 tCO$_2$-eq per tonne of fibre.

Rüter et al. [47] quantified the carbon substitution factors for viscose replacing PET, recycled PET, and polyamides for the EU wood-using scenarios. CSFs for the production and end-of-life phases for viscose of European origin were assumed to be 4.9 tCO$_2$-eq per tonne of viscose.

The question of what material wood-based textiles replace is important. Are they replacing cotton or polyester, and do they replace primary or recycled materials? Also, it is relevant if the energy consumed in production of alternative materials is generated by using coal, renewable energy sources, or mixture of energy sources corresponding to the average energy profile in a region. Arguments leading to different recommendations can be expressed. The
shortage of land has started to hinder the expansion of cotton production, and cheap oil-based textile materials are growing rapidly [56]. Wood-based fibres, cotton, and any recycled materials all help to mitigate the growth of the use of virgin oil-based materials. Hence, we argue that oil-based virgin fibres should be considered a reference material for MMFC, instead of cotton or an ‘average fibre’.

The dissolving pulp mills tend to have capacities of 200 kt/a, or more, and require 1 Mm³, or more, of wood fibre annually. That sets some constraints on the possibilities for establishing production in Norway. Directing even one third of the wood exports (Table 2) into the production of textiles fibres at a scale of 200 kt/a would give substitution benefits of almost 1 Mt CO₂ when replacing oil-based fibres. It must also be noted that several new technologies for producing wood-based textile fibres are under development [63], [64]. They use less wood, have lower CO₂ emissions, and come with higher CSFs than current MMFs [64].

3.3.3. Wood-Based Insulation Materials

Storage

Wood fibre insulation contains 80–95 % wood by mass, supplemented by additives such as water and flame retardants. We used the wood contents and densities for the products specified in Environmental Product Declarations (EPD) to estimate the carbon content per cubic meter of insulation material for a variety of European manufacturers, assuming a 50 % carbon content in wood. It varied between 0.020 and 0.079 tC/m³ for wood fibre boards and 0.014 and 0.017 tC/m³ for blown-in wood fibre (Table 1). The differences in density explain the wide range for boards. The EPD’s assume the average lifetime of 60 years which equates to a half-life of 42 years, which could include reuse if the insulation is free of damage. At the end-of-life stage, wood fibre insulation can be incinerated for energy production.

Substitution

Schulte et al. [52] made a comparative life cycle assessment for wood fibre, expanded polystyrene insulation (EPS), rock wool insulation, and some natural fibres. Based on their results, we calculated the CSFs for wood fibre for these alternatives using Eq. (4). Substituting non-renewable insulations materials with wood fibre had the largest substitution factors: 1.65 tC per tonne of product for EPS and 0.65 tC per tonne of product for rock wool.

Suter et al. [10] estimated CSF for soft fibre board insulation replacing rock wool and polystyrene for Switzerland. The CSF over the life cycle varied between 0.0027 and 0.0109 tC per m³ of used in case of rock wood, but 0.29 tC per m³ of wood used in case of polystyrene.

Rüter et al. [47] examined GHG emissions of wood fibre insulation board compared to those of aggregate of rock and glass wool, polystyrene, and polyurethane based materials. The CSF of the production phase of wood fibre was estimated to be negative at –0.11 tC per tonne of product, while the CSF for the end-of-life phase was calculated to be 0.31 tC.

The data above show a wide variation in the CSFs depending on the wooden product itself and the non-wood product replaced. To focus on Norway, we calculated the CSFs for the production phase of wooden fibreboard and blow-in insulation materials in cases where they replace mineral wool (Table 5). We used the data from EPDs for this purpose [50], [51], [65]. For the board, the CSF ranged from 1.38 tC to 4.05 tC per tonne of product, whereas for the blow-in fibre, the CSF was between 1.28 tC and 1.66 tC per tonne of product, depending on the GWP of mineral wool.
The recently built production facility for insulation material in Norway uses 75,000 m³/a of spruce chips when producing at its full capacity of 40,000 t/a [31]. Even at this moderate scale and ignoring the end-of-life benefits owing to incineration, the annual substitution benefits amount to the range from 0.18 Mt CO₂-eq to 0.59 Mt CO₂-eq. The same amount of chips could produce, for instance, around 30,000 t of mechanical paper pulp (wood use 2.43 m³/t) or newsprint made of it, both with substantially shorter lifetimes and lower CSFs (Tables 1, 3 and 4).

4. DISCUSSION

This study presents data on carbon storage and substitution factors that can be utilized to assess the climate change mitigation impacts of harvested wood products in Norway. However, the data summarised in this paper could also be helpful for the cases of other countries. An important question that the user of the CSF data should decide is what alternative materials or feedstocks the different harvested wood products substitute. We argue that, for instance, when considering textiles, the choice should be made against man-made synthetic fibres.

Many uncertainties of the parameters must be kept in mind and handled appropriately when applying the figures. For example, if we apply the lowest and highest carbon substitutions factors from Tables 4–5 to the forest industry production data in Table 2, the substitution impacts of domestic production in Norway in 2020 ranged between 2.9 and 7.7 Mt CO₂ (with an average 5.3 Mt CO₂, or 1.4 Mt C in terms of carbon). This calculation included substitution benefits from cradle to the grave. The substitution impacts from the forest industry production made of roundwood exported from Norway would come on top of these figures.

Harvesting wood for HWPs affects the forest carbon stock, which depends on various factors such as location, timing, quantity, and the type of roundwood harvested, as well as the forest management practices employed [66], [67]. Therefore, when analysing the total climate change mitigation potential in the forest sector, carbon stock projections from a suitable forestry model should also be included. In Norway, there exist a recent forest simulation model [68] that could be used for such analyses.

When considering the assumptions of energy-related emissions behind the CSFs, studies sometimes apply the GHG content of the average energy mix or the average fossil energy mix in the region [8], [23]. As the average GHG content of energy is decreasing with the increasing share of renewables [7], CSFs would also decrease over time. The concept dynamic substitution factor is used to refer to this phenomenon. Such time-dependent CSFs have been considered e.g., in [69]–[72]. One could argue that if most of the consumed energy in the relevant regional scope is not coming from GHG free sources, a need for further decreases in fossil-based energy production remains. Then the least favourable marginal energy source – the one that the society strives to face out – could be considered as benchmark energy source in calculations. A decline in the energy use owing to of HWPs with positive CSFs would help to diminish the use of most pollutive energy sources and decrease the need to invest in new renewable energy.

The EU’s waste legislation is enforcing increased recycling and recovery of municipal waste including paper, textiles, wood materials, and packaging [59]. Increasing amounts of materials would be reused and incineration in the end of the life cycle, when further recycling is not possible, would also occur more likely than landfilling. That should affect the GHG emissions and lifetimes of both wood and non-wood materials in the future.

The carbon substitution and storage factors can be used to assess the climate impacts of current or plausible future uses of wood. Exogenously defined alternative wood use scenarios
have also been compared [9], [20], [69]. The hypothetical nature of such scenarios should be kept in mind. In the global markets, exogenously pushed changes in a supply from one region would partly be offset by the production adjustments in other regions [73]. Regarding products, for which there is a clear growth potential, such leakage phenomenon should be weaker. This might be the case with the products considered in more detail in this study: wood-based textiles and wooden construction and insulation materials.

The literature of the climate impacts of HWPs barely covers new or emerging end-uses of wood for which further examination on plausible assumptions is needed. Wood-based protein for fish feed [74], [75] could be an interesting HWP for Norway. However, its production seems not to be profitable in Norway at today’s technologies [31].

In the further analyses, we will consider the current and future production palette of the Norwegian forest sector in more detail and evaluate the carbon storage and substitution benefits while accounting for the changes in forest carbon pool.

5. CONCLUSIONS

Carbon storage and substitution parameters for harvested wood products are subject to significant uncertainties. However, the data suggest that there are several end-uses of forest products that provide clear substitution benefits, in some cases coupled with long-term carbon storage. Sawnwood used as construction material, wood-based textile fibres, and wood-based insulation materials are examples of products that seem attractive in bioeconomy transformation of the Norwegian forest sector. These products have the potential to replace more environmentally harmful materials in growing markets, and their production could be increased in Norway without causing considerable production adjustments in other countries.

Sawnwood is an essential product for the Norwegian forest sector and its production is in increase. It can continue to provide a basis for the climate-friendly bioeconomy. Processing sawlogs to sawnwood generates sawmill residues as a by-product. If an increasing share of these by-products and pulpwood were processed to textile materials as substitutes for oil-based fibres, clear emission-savings would be realized. However, the carbon storage time of textile materials is currently short. Wood-based insulation materials are another emerging product with market potential. They offer longer lifetime for carbon and higher substitution factor than most other products made from small-sized wood and chips do.

Making a cautious estimation, the carbon substitution impacts of domestic production in Norway in 2020 can be estimated to range between 2.9 and 7.7 Mt CO₂. Additionally, based on the default values and processes used in climate accounting, the mean lifetime of carbon remaining in the harvested wood products produced in Norway could be approximately 17 years. By shifting the roundwood that is currently exported or used in the production of HWPs to the production of climate-smart products, it is possible to increase the substitution benefits and extend the carbon storage time. However, a detailed analysis of the market possibilities and benefits of alternative pathways will require further study and investigation. The data presented in this article could be used for such analysis.

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