Cross-laminated timber constructions in a sustainable future – transition to fossil free and carbon capture technologies

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Abstract. Cross laminated timber (CLT) has recently increased in use as a building material for low carbon design and is often applied in small and multi-story buildings. Several studies have shown lower fossil related greenhouse gas emissions than alternatives, but the life cycle emissions vary substantially between different CLT producers. These emissions are mainly indirect and thus climate change mitigation could reduce these emissions. Previous research shows that that biofuels and carbon capture and storage (CCS) are technologies that have the potential to reduce the climate impacts of the CLT life cycle. This study assesses the impacts on climate change from CLT with these technologies within the framework of environmental product declarations (EPD). In the short run, switching to fossil free fuels provides a reduction in the carbon footprint of CLT. In the long run, CCS at the end-of-life of CLT buildings can provide a net negative carbon footprint over the life cycle. This assessment on the use of CLT is mainly related to the Sustainable Development Goal SDG9: Industries, innovation and infrastructure and the indicator for CO2 emissions per value added, so the assessment in this paper is mainly focused on this goal. SDG7: Affordable and clean energy and SDG15: Life on land are also relevant.

1. Introduction
Cross laminated timber (CLT) is produced by sawn timber and adhesive, and is applied for walls and floors as a structural building material. CLT has been used in tall timber buildings as an alternative to concrete and steel. Several studies have shown lower fossil related greenhouse gas emissions than alternatives, but the life cycle emissions also vary substantially between different CLT producers. These emissions are mainly indirect and climate change mitigation actions in society will certainly reduce these emissions. The use of wood raw materials also influence climate change through temporal biogenic carbon storage, but carbon capture and storage technologies for waste incineration can make it a permanent carbon storage within the life cycle.

Most work on LCA on CLT focuses on current technologies for the life cycle impacts, but there are several research publications on the methodological aspects of LCA of wood products [1]. This paper focuses on the LCA within the framework of EN 15804, to assess the potential of new technologies that are on the market or soon implemented.

Guest et al. [2] assessed the inclusion of biogenic carbon storage effects on climate impact, on a range of bio-product systems. The results showed that products from Norway spruce with long life time (140 years) or used as biochar and CCS will have a negative GWP factor. For CLT, this is then a potential for having a negative global warming potential (GWP) from both the potential long life time of the buildings and if CCS is applied at end-of-life. Guest et al. [2] also show, however, that when the
dynamics of biogenic carbon storage is included, the impacts on GWP from bioenergy can have a factor of up to 0.5 compared to fossil GWP emissions on a 100 year time horizon.

The main sustainable development goal (SDG) with relation to the results of this work is SDG9 on industry, innovation and infrastructure, while SDG7 Affordable and clean energy and SDG15 Life on land are also seen as relevant. Within the SDG9, the indicator 9.4.1 is the most relevant and measures the CO₂ emission per unit of added value. For SDG7, the indicator 7.2.1 on renewable energy share in the total final energy consumption is quite relevant as CLT is utilized for energy recovery at end of life. For SDG15, the most relevant indicators are 15.1.1 on forest area as a proportion of total land area, 15.1.2 on proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas and 15.2.1 on progress towards sustainable forest management. Within the assessment of this paper, the SDG9 will have the main focus, but the relation to SDG7 and SDG15 will be discussed for further reference.

The objective of this paper is to show the effects on the life cycle impacts of CLT when technologies for fossil free transport and carbon capture and storage are applied. The case study on CLT, biofuels and CCS are further explained in the rest of the introduction.

1.1. Cross laminated timber case study
Cross laminated timber has grown in application the last years in Norway and internationally. Most of the CLT on the Norwegian market was previously imported to Norway, but in 2019 the world's largest CLT factory opened in Norway. The manufacturing of cross laminated timber and glued laminated timber are quite similar in inputs and outputs, so the LCA results for the product per cubic meter are typically quite similar. Tellnes and Nore [1] compared applicable EPDs available in Norway and found that GWP with instant oxidation of biogenic carbon ranged from 60-130 kg CO₂-eq/m² in the life cycle module A1-A3. From the development of these EPDs, it is known that the use of diesel in forestry and transport are the main contributors. There are some exceptions when manufacturing is in a country with high emissions from electricity production.

There have been tests of using biofuels in forestry and for transport to building sites. Hence, this technology seems quite available, but it is limited by costs. At the end-of-life of CLT, the EPDs so far assume waste incineration with energy recovery [3]. There are however plans to install carbon capture and storage at a municipal waste incinerator and the technology has been tested to be working. Yet again, the price is higher, and the Norwegian Government is planning to make the investment decision in mid-2020. The use of CCS has previously been assessed on treated wood and showed a potential large negative GWP for the full life cycle of the product when biogenic carbon is included in the GWP calculations [4].

1.2. Biofuels for transport
Biofuels are applied with the specific purpose of reducing transport related carbon footprint. Raw material sources for biofuel production are many, and several are of concern. Organic waste sources are considered the safest option in a carbon emission perspective, but cannot supply the total fuel requirement. Soy oil, palm oil and rape seed oil are some of the most common raw material biofuel sources. Palm oil and soy are highly controversial because they may be connected to a type of plantation activity that severely harms tropical forests, with massive impact on biodiversity. Tropical forests also act as means of carbon storage, which for plantation activity is much lower. Carbon emissions from land use change are therefore particularly high for palm and soy oil. Rape seed oil, sugar beet, sugar cane and other temperate oil or sugar growths compete for the same agricultural land as human and animal feed. Land originated biofuels cause increased pressure on agricultural land, especially in developing countries, many of which lie in tropical areas, and also contribute to higher pressure on forest and natural areas. To combat the many adverse effects of land-based biofuels, Norway demand by law that advanced biofuels be used to some extent [5] §3-4. Norway also have restrictions on land type use available for biofuel production [6] §3-7 and §3-8, and strict documentation for carbon footprint improvement compared to fossil alternatives [6] §3-6. The share of
biofuels in petrol and diesel was regulated to a minimum of 12% in 2019 and 20% within 2020 [5] §3-3. The blend of advanced biofuel had to be above 2.25% in 2019 and increased to 4% within 2020.

Biofuels can be used in most current diesel driven machinery. Using B100 (100% biodiesel) may require some minor modification of engine and the engine fuel feeding program. For other biofuels like E100 (100% ethanol), biogas or bi-/tri fuel (biogas and liquid fuel) a total modification of engine and major modification of vehicle is necessary [7]. Costs are thus greater for changing fuel type rather than converting to 100% biodiesel. However, in some instances the net cost over the vehicle lifetime might in fact be negative when switching to biogas, due to lower fuel costs [7]. To determine net cost, the price per energy unit and engine efficiency are the most important parameters in addition to capital costs [7].

Infrastructure and vehicle manufacturing for fossil fuel driven diesel lorries contribute to about 12% of the total transport carbon footprint. As less carbon intensive fuels are used the relative contribution of infrastructure will increase. Production of fuels, exhaust emissions and production and end of life of infrastructure and vehicle are all key to investigate a holistic all-encompassing transport LCA. To investigate transport at product level specific capacity utilization, vehicle type, EURO class and fuel type the specific supply line in question must be used. With a global decreasing capacity utilization trend [8] more vehicles, road maintenance and infrastructure are needed per unit of freighted good.

1.3. Carbon capture and storage
In Norway cross-laminated timber is typically combusted in the end of life phase, and in isolation this causes substantial emissions of CO₂ to the atmosphere. If these emissions can somehow be avoided, the LCA climate footprint of the product will be lower. This reduction will be manifested in the LCA model whether or not biogenic carbon is used. Carbon capture and storage involves capture, transport and long-term storage (sequestration) of CO₂. A comprehensive review of LCA studies of CCS by IEAGHG [9] shows that CCS serves to decrease the GWP, as a substantial mass flow of CO₂ is directed to an underground storage facility rather than to the atmosphere. However, impacts related to all other environmental categories (acidification, eutrophication, etc.) increase when CCS is implemented, due to an increase in technological activity. This activity also reduces the climate change mitigation efficacy of CCS. In ideal terms, geological CO₂ storage is a final storage of CO₂. In reality, however, the efficiency of such storage at longer time scales is uncertain. In existing LCA studies one nevertheless often assumes 100% storage of the CO₂ gas. Many studies of CCS have concerned coal power plants and one such plant exists in Canada, but CCS can also be applied to fuels with biogenic sources and can then give net sequestration of CO₂ in what is known as bio-CCS.

Carbon capture and storage has been applied since 1996 in the Sleipner oil field off the coast of Norway where the removal of CO₂ from natural gas are pumped back into the underground reservoir. This was initiated as a result of taxes on CO₂ emissions. For the last 10-15 years, there has been high activity on R&D on CCS. The first goal was to apply it on combined heat and power plants, but these plants have an uncertain future and therefore the goal now is presently to install CCS at cement production and/or waste incineration. These facilities have tested successfully the capture technologies and the full-scale plants are now specified so that the parliament can make an investment decision in mid-2020.

2. Methods
A life cycle assessment model from previous development of environmental product declarations (EPD) according to EN 15804 for CLT was updated for the new factory data and with two additional scenarios for biofuel and CCS. The functional unit of the study is:

1 m³ of cross laminated timber, from cradle-to-grave and with a reference service life of 60 years.
The life cycle modules included are from cradle-to-installation (A1-A5) and the waste processing (C3) and disposal at end-of-life (C4), in addition to benefits and loads beyond the life cycle. There are three scenarios for this life cycle:
1. Reference – typical CLT as calculated for EPD in 2019
2. Biofuel – all transport fuels are changed to 100% biofuel
3. CCS – carbon capture and storage are applied at the end-of-life

2.1. Life cycle inventory data
The inventory of CLT is from previous work on development of EPD for CLT and was updated for a new factory that was officially opened in 2019 as the largest production site in the world for CLT. The scenarios beyond cradle-to-gate represent a building site in Norway’s capital Oslo and the currently most common practice at end-of-life: incineration with energy recovery. The modules and main unit processes of the LCI are shown in table 1.

| Module | Main unit processes |
|--------|---------------------|
| A1-A3 | Product stage |
| A4  | Transport to building site |
| A5  | Installation |
| C3  | Waste processing |
| C4  | Waste disposal |
| D   | Benefits and loads beyond the life cycle |

Table 1. Life cycle modules and main unit processes in the study

In 2018 the Norwegian biofuel production mass turnover was 87.2% biodiesel/bio-oil and 12.8% bioethanol. Annual import of palm oil as a fuel source was reduced from 317 mill litre in 2017 to 93 mill litre in 2018 and its prevalence as a biodiesel constituent dropped from 52% to just about 24.8%. Soy oil makes up 6.8% and animal biproducts 3.5%. In total, 41% of biodiesel consisted of 2nd generation feedstock sources [10]. The energy content of biodiesel is estimated to 34.6 MJ / kg [11] whereas diesel has 36.2 MJ / kg [12]. Lower energy content means that more mass is required for the same energy output. This amounts to +4.5% higher fuel consumption rates of B100 and +0.9% for B20. Lorries freighting timber have increased in maximum weight allowance from 56t to 60t over the last decade. However, some Norwegian roads have lower maximum weight allowances and new test projects aim to assess the use of even larger vehicles of 74t maximum weight allowance.

Data for carbon capture was based on a study for CCS on waste-to-energy in Norway [13], and the energy used in the capture stage was here assumed to be the covered by the amount of electricity recovered from the incineration of CLT at end-of-life. Module D inventory in CCS scenario therefore has no benefit from substituting grid electricity. The modelling of carbon storage and allocation in modules is from a previous study on CCS on treated wood [4].
2.2. Life cycle impact assessment

The impact assessment only applies for climate change and the indicator GWP-total from EN 15804 [14], which is based on the GWP100 IPCC2013. The sub-indicators for climate change in EN 15804 (CC-fossil, CC-biogenic and CC-land transformation) were however replaced by sub-indicators for instantaneous oxidation of biogenic carbon (GWP-IOBC) and the contribution of biogenic carbon content (GWP-BC), where the sum of GWP-IOBC and GWP-BC is equal to GWP-total. GWP-BC equals the CO₂ emissions from complete oxidation of the biogenic carbon content. The indicators have been applied in previous case studies [15] and are part of the PCR applied in Norway for CLT.

3. Results and discussion

The results are presented in figure 1 and show that switching to fossil free biofuel can give some reduction of GWP in the value chain, but it needs to be addressed throughout the whole value chain from forest, log transport, sawmilling and transport to CLT manufacturing. The greatest carbon footprint reductions are linked to carbon, capture and storage technologies. The benefits beyond the life cycle in module D are for Norway relatively low compared to other countries because of the high share of renewable energy in electricity and district heating. The use of biofuels reduces the benefits slightly as the secondary fuels applied in the biofuel mix, while the CCS scenario also has some reduced benefits because of the use of recovered energy from waste incineration at end-of-life of CLT for carbon capture. The impact on climate from transport to building site (A4) and installation (A5) are rather low in this case. The transport to building site scenario is for a building site about 100 km away, so larger distances could increase these impacts substantially and previous cases has shown these at the same level as production of the materials (A1-A3) [3].

![Figure 1](image)

**Figure 1.** The results on climate change indicators for the three scenarios shown per life cycle module and as a sum of the life cycle modules included, in addition to benefits beyond the life cycle.
3.1. Contribution analysis unit processes in reference study
The contribution to GWP-IOBC are shown in figure 2. The results show that harvesting has the largest contribution followed by forwarder, log transport and sawn wood transport. The contribution of the harvester is having a multiplication effect because of the economic allocation between sawlogs and pulpwood in forestry, in addition to the economic allocation at the sawmill between sawn wood and chips sold.

![Figure 2. The contribution to the GWP-IOBC indicator from the main unit processes in A1-A3 in reference scenario](image2.png)

3.2. Sensitivity analysis – transport
A sensitivity analysis was performed to show the importance of vehicle size of log transport (56 ton, 60t and 74t) and the share of biofuel from 0 %, 20 % and 100 % (B0, B20 and B100). The results are presented in figure 3 per tonne-kilometre (tkm) of transport.

![Figure 3. Biodiesel blends for 56t, 60t and 74t allowances for timber lorry per tkm and the impact to the GWP-IOBC indicator](image3.png)

The results show lower impacts of GWP for B20 or B100 biodiesel compared to B0. In the case of 60t timber lorry (current limit) GWP-IOBC from B20 compared to B0 decrease by 7.7% whereas B100 can potentially cut 40.1%. The delta difference between B0 and B100 show the maximum cuts achievable by changing to biogenic diesel fuel of the 2018 biodiesel blend. Further cuts require other means such as reduced fuel consumption, increased share of 2nd generation biofuel sources etc.
GWP cuts allowing 74t B20 vehicle compared to the 2020 allowance and fuel requirement cut 25.3% of timber transport emissions per tkm solely by fuel reduction per tonne timber freighted. GWP cuts by biodiesel introduction will be slightly greater for a smaller vehicle (56t) and oppositely lower for larger vehicles due to lower fuel consumption rates per tonne timber freighted. The greatest GWP cuts comes when using biodiesel in the larger vessels compared to fossil fuel in smaller vessels. The larger the vessel the greater the GWP reduction compared to status quo. For regular road transport of wood products (A2 and A4) the reduction potential going from B0 to B100 is estimated to 33.8%, which is somewhat less than for timber trucks. A load factor of 35% instead of 30% contributes to significantly lower GWP per tkm. Load factor trends should also transfer to timber lorry.

Figure 4. Biodiesel blends and load factor variations on road transport impacts for sawn wood from sawmill to CLT factory (A2) and CLT factory to buildings site (A4)

3.3. Contribution analysis - Carbon capture and storage

The scenario of carbon capture and storage showed a large reduction of the GWP-total due to the final sink of biogenic carbon in the CLT. The modules C3 and C4 did however increase slightly on the GWP-IOBC indicator and the contributions to this are assessed here. For module C3, the main contributions are shown in figure 5. Carbon capture requires production of chemicals for the process and these are the main causes of the increase. The CCS reduces not only GWP-total, but since the adhesive is fossil based, it also reduces the GWP-IOBC indicator. For module C4, this includes transport and storage of carbon dioxide in addition to landfill of ashes. The results are dominated by the transport of carbon dioxide by sea which gives about 6 kg CO2-eq. per cubic meter of CLT.

Figure 5. The contribution to the GWP-IOBC indicator from the main unit processes in C3 with CCS
4. Conclusion
In the short run, switching to fossil free fuels can provide reduction in carbon footprint of CLT. In the long run, carbon capture and storage at end-of-life of CLT buildings can provide a net negative carbon footprint over the life cycle. Biofuels show reduction in the GWP indicator for EPD and is relevant for the SDG9, but use of biofuels is also a challenge for biodiversity and thus for SDG15 on life on land. However for SDG 7, CLT contributes to renewable energy from byproducts and waste.

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