Ole Christian Stene Ingul
Alistair Hutton Street

Bachelor's thesis

Modelling Circular Timber Products in Norway: The environmental impact of circular economics applied to Norwegian timber products.

Environmental impact of circular timber product

June 2022

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Foreword

The bachelor thesis is written at the Institute of Commodity Production and Structural Engineering (IVB) by the Faculty of Engineering Science at Norwegian University of Science and Technology (NTNU). This thesis is written as part of the bachelor programme, Bachelor in Structural Engineering.

We want to start by thanking the contributors to this study, associate professor Lizhen Huang and our contact in the Industry, Per Johannessen from Ragn-Sells. This study would not have been feasible without their guidance, feedback and the data they have contributed.

Abstract:

This study sets out to inform the Norwegian timber industry of possible reductions in environmentally damaging carbon emissions achieved through the introduction of circular economics. The main findings of the study are that for a group of eight common timber products produced in Norway an adoption of 10% closed loop (re-use) circular economy could result in more than 200% reduction in carbon emissions for those products. Further, that the emissions from current practice in Industry are lower than the reported emissions in the EPDs (Environmental Product Declarations) for those eight products.

There a few papers published concerning how emissions will be adapted from a circular Norwegian timber industry. EPDs and their assessment of net emissions from a timber product are based on incineration of the product at end-of-life. By compiling a database of Norwegian products with EPDs covering end-of-life data, a group of eight easily re-usable solid timber products were identified and analysed in a life cycle analysis (LCA) of each product. A waste scenario reflecting practices used in current industry and based on primary data from industry was modelled in Simapro software. This allowed modelling of waste scenarios for the eight products with different levels of open loop and closed loop recycling modelled for each product.

This paper shows that Norway has a chance to take a leading role in circular timber processing. That with the current infrastructure and small changes in current practices, significant reductions in carbon emissions can be achieved. Society needs do more with less to become more sustainable. This study shows how the Norwegian timber industry may be able to help towards that goal.

***Abstrakt*:**

Denne studien ønsker å belyse hvordan en reduksjon I karbon-utslipp kan oppnås I Norsk byggebransje ved å implementere et sirkulært økonomisk system. Det er tatt for seg en gruppe på åtte vanlige treprodukter produsert i Norge, og det er funnet ut at en reduksjon på opptil 200% karbon-utslipp er oppnåelig ved å gjenbruke 10% mer enn det disse produktene blir i dag. Videre er det funnet ut at utslippene fra dagens praksis I industrien er lavere enn det som er rapportert I EPD-ene (European Product Declaration) for dise åtte produktene.

Det er til nå få studier som er pulpiest runt utslipps-endring fra Norsk bygge-bransje ved overgangen til en sirkulær økonomi. I EPD-ene er vurderingen av utslippene fra produktet basert på at det brennes ved enden av livsløpet. Ved å skape en database av åtte lett gjenbrukbare, heltre-materialer med EPD-er som dekker «end-of-life» data fra materielaene, er det klart å analysere og identifisere hvert av de mest egnede materialene gjennom LCA-analyser Et avfalls-scenario ble skapt basert på dagens metoder for avfalls-håndtering og primær-data fra industrien ble brukt til modellering i Simapro. Dette gjorde det mulig å modellere scenarioer med forskjellige nivåer av «closed-loop» og «open-loop» gjenvinning for hvert produkt

Studien vier at Norge har mulighet til å ta en ledende rolle innenfor bygge-bransjen når det kommer til gjenbruk av tre. Med dagens infrastruktur og små justeringer av nåværende praksis så vil det være mulig å redusere karbon-utslippene fra næringen med en betydelig mengde. Dagens samfunn må klare å gjøre mer med mindre for å bli mer bærekraftig i måten de lever på, og denne studien viser at Norge kan ha muligheten til å hjelpe mot dette målet.

Key words*:* Life cycle assessment, circular economy, Norway

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1.0 Introduction

This study aims to fill the gap in knowledge of whether the global warming potential of Norwegian timber products can be reduced by introducing circular economy to the industry. It seems to be intuitive that re-using the timber from one building to build its replacement, will result in lower carbon emissions. However, we are aware of no published studies on this topic. This paper sets out investigate, with reference to robust, relevant and recent data from Norwegian sources, whether a circular timber industry in Norway can significantly reduce carbon emissions using the technology and infrastructure currently available.

The need for a reduction in carbon emissions, and the usefulness of circular economy in achieving this aim, will be set out in a literature review. A summary of Norwegian timber products on the market with available Life-cycle Analysis (LCA) data will be compiled in a database. Raw data on the current practices and technology used in recycling timber products will be used to model an LCA of the recycling process. Using this LCA, models of possible circular process streams (by variation of waste reduction and management) can be compared, and conclusions drawn on GWP emissions of Norwegian timber products.

The purpose of this study is to provide information for active parties in the industry, keen to improve the carbon emissions from construction. This investigation aims to provide data to assess the intuitive argument that the re-use of the resources already contained within the built environment is a way of making construction cleaner and greener.

1.1. Purpose and Problem Statement

The purpose of this study is to provide information to the Norwegian timber industry on whether introducing circular economy to the industry can reduce carbon emissions.

Further, whether optimising current technology and practices can result in significant reductions in carbon emissions from the Norwegian timber industry.

1.2. Explanation of Terms and Definitions

EU: European Union

UN: United Nations

IPCC: The Intergovernmental Panel on Climate Change.

SDG: Sustainable Development Goals.

GWP: Global Warming Potential

BREEAM: Building Research Establishment Environmental Assessment Method

Circular economy: Economic system that replaces the end-of-life concept, by reducing the use of, and recirculating resources in production, distribution and consumption processes.

LCA: Life Cycle Analysis, the analysis of the environmental impacts of a product taking into consideration the cumulative impact on the environment of all unit processes involved with the development, production, use, and end-of-life management of that product.

EPD: Environmental Product Declaration. A standardised document showing the environmental impact of the product. The document is based on an independently verified LCA under ISO14025.

PCR: Product Category Rules. The framework of rules for EPDs to provide the same information on the same impact categories and therefore provide comparability.

2. Literature review

This chapter will review existing literature and investigate the foundation for circular timber-products. The literary review consists of three main parts: Sustainable development, Circular economy, and lastly possible challenges regarding recirculated timber. Finally, how the investigated literature creates a theoretical foundation to answer the study's problem statement.

2.1. Sustainable Development

The term sustainability is currently defined as *"the ability to be maintained at a certain rate or level" (Oxford Languages, 2022)*. Its origin comes from the forestry industry where it referred to how the level of deforestation should not surpass the volume that is regrown. In Norway the term has been commonly used since the late 1980's and after the World Commission on Environment and Development published the report "Our Common Future" in 1987, the term evolved into sustainable development. "Our Common Future" would become important for politics regarding environmental questions and how it denoted environment, economics and social development. The report concluded that the current generation must secure their own current needs without compromising the needs of future generations, which has been a recurring theme in the UN's work towards sustainable global development.

2.1.1 UN's impact on sustainable development

This section describes the timeline of the development of the UN's sustainable development goals. Below is a list of significant developments by date.

1972 – Stockholm

United Nations conference on the Human Environment – The first conference on a global scale to have environment on the agenda as a major issue (UN, 2016b).

1983 & 1987 – Our Common Future

World Commission on Environment and Development – The commission was created and lead by Norway's former prime minister Gro Harlem Brundtland. The task of this commission was to propose solutions that could contribute to resolve environmental and poverty issues (Gro Harlem Brundtland, 1987).

Our Common Future was released in 1987 which included the term sustainable development for the first time. The report changed how the world looked at development and environmental issues.

1992 – Rio de Janeiro

United Conference on Environment and Development – Agenda 21 was prepared and agreed upon amongst the member states. Agenda 21 was intended to be a guide for sustainable development in 21st century and identified the developed countries production and consumption-patterns as well as showing how these countries could reduce the environmental impact from these patterns (UNCED, 1992). It also encouraged advances in developing countries, but with a sustainable perspective (UN, 2016a).

1997 – Kyoto Protocol

A protocol that included specific goals and deadlines regarding a cut in greenhouse gas emissions for developed countries, as well as penalties for noncompliance. It was adopted in 1997 but didn't take effect until 2005 and was supposed to last until 2012. The protocol was adopted for a second period starting in 2013 and ending in 2020 (UN, 2015b)**.**

2000-2015 – Millennium development goals

Eight international goals were established with the aim to reduce poverty in developing countries. One of these eight goals emphasised sustainable development (UN, 2015a).

2002 – Johannesburg (Rio + 10)

World Summit on Sustainable Development – This meeting included discussions on plans to achieve the goals set out in Rio de Janeiro in 1992, as well as securing sustainable development with focus on water, health and energy among other concerns (UN, 2016c).

2012 – Rio de Janeiro (Rio + 20)

United Nations Conference on Sustainable Development – A meeting where world leaders developed a road map for how the goals from the 1992 summit could be met. This involved the creation of a set of sustainable development goals anchored in the millennium development goals from 2000 (UN, 2012).

2015 - Paris

The Paris Agreement - a treaty that replaced the Kyoto Protocol, and functions as a binding agreement between the worlds countries to limit climate change. More specifically, leaders agreed to keep global warming below 2°C and work towards a total increase of 1.5°C. Norway furthered a goal to reduce climate gas emissions from 50 to 55% within 2030

(Regjeringen 2020a). The UN member states also agreed upon 17 goals for sustainable development (UN, 2017).

Figure 1- UN Sustainable Development Goals (UNGDP, 2015)

To reach these goals it is necessary to ask questions on how current infrastructure and way of living can be changed for the better

2.1.2 Sustainable development in Norway

The Norwegian Internal Control Regulations from 1981 aim to promote improvement in Norwegian industry by securing a systematic implementation of measures, which extend to how the environment is impacted, and the improvement of waste management (Lovdata, 1983).

In 1992 the Norwegian environmental paragraph, §112 (miljøparagrafen), was unanimously adopted by the parliament and anchored in the constitution. The paragraph secured peoples' and nature rights for current and future generations (Jacobsen, 2014). The pollution control act from 1996 constitutes that all pollution is prohibited and that a precautionary principle should be assumed when dealing with anything that may produce pollution (Lovdata, 1983).

In 2005, after a political agreement between the governing parties to be, they produced a declaration known as the Soria Moria declaration (Soria Moria Erklæringen). Here it is stated that Norway will become a pioneering country regarding environmental politics, meaning that it will be based on a sustainable development principle and extends to the protection of vital environmental and natural resources (Stoltenberg J. , 2005). In 2018 the Norwegian climate law took effect, and the purpose of this law is to further the implementation of the country's climate goal and ensure that an open debate on direction and status regarding this work is maintained. The law also states that it shall not become a hindrance to reaching the goals set in cooperation with the EU (Lovdata, 2018). In the Paris agreement Norway committed themselves to reduce greenhouse gas emissions by at least 50% by 2030 in addition to working towards the UN's Sustainable Development Goals (Regjeringen, 2021). In order to achieve this, an active approach to domestic climate politics has been developed, the aim is to cut emissions and simultaneously maintain the country's economic growth.

Considering how most of the world's countries are committed to becoming more sustainable through the Paris agreement, it may be advantageous for Norway to take a leading role regarding sustainable development in the future. Building competence on sustainability will be valuable for Norwegian resources as well as giving domestic companies an upper hand in European economic competitions (Regjeringen, 2021).

2.1.3. Sustainable development in the construction industry

Within the construction industry, a sustainable approach to building has been around for some time already, for example, the certification tool Building Research Establishment Environmental Assessment Method (BREEAM). Tools like this focus on raising awareness regarding material choices, but it does little to further the development of a circular economy in the Norwegian construction industry. This tool, and those similar to it, are not required on all buildings, though many new public projects use this tool to rate the sustainability of those projects. The results from this paper will hopefully add to knowledge regarding whether it is more sustainable to use products in a way that they can be re-used again after the project is dismantled in a way that use little to no technological input.

2.2. Circular economy

Circular economy is a term that builds upon circular cycles found in nature and refers to an economic system where every resource is reused and won't produce waste (Nilsen, 2020). This concept is not new, regarding the utilization of resources, the term may fit better on prehistoric civilisations. Over time, developments in technology and quality of life have led to something that resembles a linear structure, which has resulted in more single use of resources and therefore more waste (Stahel, 2019). Today, overconsumption of resources is commonplace compared to what is considered sustainable. Industry is beginning to recognise that it is time to do more with less. The construction industry is recognising that it is necessary to utilize more of the resources already bound up within current structures. Reduced resource consumption within the industry will help Norway and the global community to achieve the goals set out in the Paris agreement (UN, 2022).

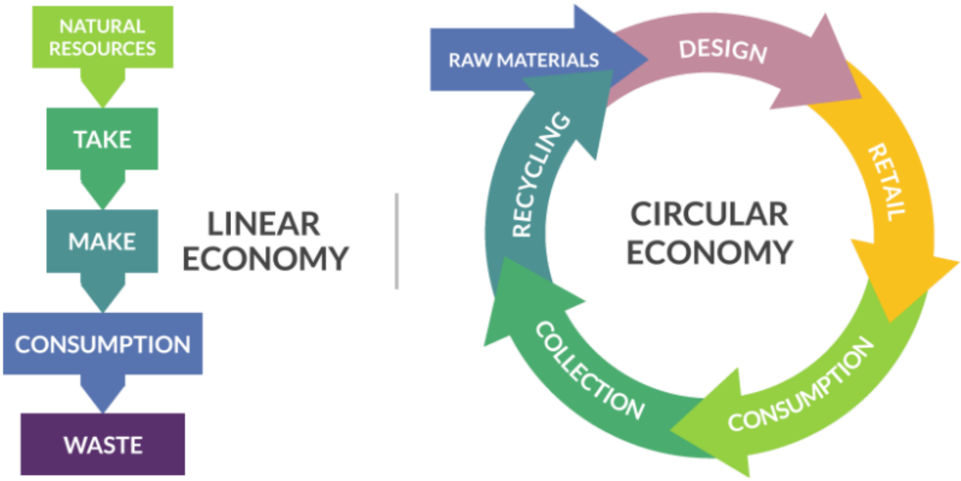

Figure 2- Graphical representation of difference between linear and circular economy (End-of-Waste-Foundation, 2019)

2.2.1. Circular economy and UN's Sustainable Development Goals

The figure below is a graphical presentation on how implementing circular economy can impact each of UN's sustainable development goals. Impact is represented by colour where the red strongly impacts, orange partly impacts, and grey has no impact (Anne P.M. Velenturf, 2021).

Figure 3 - Graphical repsentation of how circular economy impacts the UN sustainable Development Goals (Anne P.M. Velenturf, 2021)

There is little to no impact on the social goals, and a circular economy will mainly help progress towards environmental and economic issues.

2.2.2. Circular economy in construction industry

Circular economy in the construction industry focuses on using the resources available in the most effective way possible. This stands in opposition to the traditional holistic approach to sustainable construction that focuses on social, economic, and environmental sustainability (KBNN, 2022).

The construction industry in Norway is responsible for 15% of the total annual carbon emissions (Regjeringen, 2022a). Resource production and transport accounts for half of all emissions tied to a building's life cycle, and multiple projects have shown that it is possible to cut total emissions by 40-50% without huge economic repercussions, by choosing better materials and solutions, as well as reusing more and demolishing less (Byggaliansen, 2019). One of these projects is SirkTRE which aims to close the gap of knowledge and increase the viability of using, and re-using, wood in construction projects. "*The project will analyse the sustainability and environmental footprint of the wood-value chain based on strategies and new technologies that contribute to circularity" (CircWOOD, 2022)*.

According to the «Circularity Gap Report Norway», the Norwegian economy is only 2,4% circular, and that that waste from the construction industry accounts to 20% of the country's total, which suggests that the industry has an opportunity to become more circular (Marc de

Wit, 2020). In order to achieve circularity in the industry the report suggests using this waste as a resource through reversed construction, dismantling existing structures, giving them new purpose as a resource. It has also been suggested by Green Building Alliance to give economic advantages to builders who demand more environmentally friendly solutions from their contractors, as well as adapting the building codes to make the rehabilitation of structures a circular economy (Byggaliansen, 2019).

2.3. Possible challenges regarding recirculated timber

2.3.1. Legality of using recirculated timber

Norway is currently not a member of the EU, but in the EFTA, European Free Trade Association, and in environmental and recycling-politics their decisions influence Norwegian regulations. Specifically, the EU's council of ministers adapted the so-called waste package, now known as the waste framework directive, and the landfill directive, in May of 2018 (EU, 2018). These two directives have a large impact on recycling and recirculating timber in Norway (avfallnorge.no, 2018). The directives demand an increase in reuse and recycling of municipal waste by at least 65% by 2035 and wood packaging by at least 30% within 2030, reflecting the goal of furthering a circular economy in the union. They also specify that producers of products will have responsibility of the product when it becomes waste. This will hopefully lead to systemic change where industries work together, where one companies waste is another's raw material source. In June 2022 the Norwegian government changed regulations on waste, emission-reports, recycling, building codes and more. The industry is now committed to plan buildings in a way that enables the possibility to disassemble its components and reuse them (Regjeringen, 2022b), (Regjeringen, 2022c). This change primarily impacts the planning and construction of new buildings, and for the time being it's uncertain if rehabilitation-work will be adapted as well.

2.3.2. Natural decay of timber over time

If we move toward an industry with increased use and re-use of timber, the longevity of timber products is important. There are examples of wooden constructions that have maintained their structural integrity for centuries (Baker, 1969), e.g., the Hōryū-ji-temple. This suggests that wood can keep its structural integrity over time without decay, given the right circumstances. The issues arise when wood is exposed to specific levels of moisture and temperature over time. This can lead to the growth of fungi that decomposes the wood, destroying the cell walls, thus reducing its strength. *"If there should be insufficient moisture, after growth has started, the fungi do not necessarily die, but will probably become merely dormant. Active growth can start again, sometimes years later, when sufficient moisture returns." (Baker, 1969).* Regarding temperature, there are factors to be taken into consideration when choosing timber for re-use. Fungi thrive between 18-35 degrees centigrade. When the temperature is approaching freezing, growth gradually ceases until it stops, leaving the fungi in a dormant state. Growth can restart if favourable conditions return. The Norwegian climate typically varies between -15 to 40 degrees centigrade, creating challenges when choosing timber products intended for recirculation.

2.4. Theoretical foundation Summary

The theoretical foundation for this study was based on the literature presented, as well as information gathered through site-visits and considered sustainable development, circular economy and possible challenges regarding recirculated timber. The purpose of the theoretical foundation is to specify and structure information in order to help understand the problem statement.

Sustainable development has been defined and how it has been developed through politics and multiple UN-meetings. This section showed how Norway's work with sustainable development has been affected, and we investigated why the Norwegian construction industry may be a good industry to make circular. This section examined the construction industry's high contribution to emissions in Norway and how it affects waste generation and resource consumption.

The term circular economy was explained and how it ties into the UN's sustainable development goals. Further, explanation of what a circular construction industry means and why there are opportunities in this sector in Norway.

The final section discussed the potential challenges that could arise when recirculating timber. How Norwegian regulation is affected by the EU in regard to developing circular practices in Industry. Lastly, this section described how natural decay of wood works, and how the process may create challenges when choosing timber products for recirculation.

3. Materials and Methods

This chapter will elaborate on the methodology and materials used to answer the problem-statement.

The goal of this study: Whether introducing circular economy to the Norwegian timber industry can reduce carbon emissions. Further, whether optimising current technology and practices can result in significant reductions in carbon emissions from the Norwegian timber industry.

3.1. Scope of the study

The scope of this study includes:

1. A summary of unmodified solid timber products produced in Norway with EPD information on "end of life" product stages.
2. LCA of model of waste management and timber recycling in Norway, where the product is harvested, used and produced in Norway.
3. A comparison of the GWP of the product as represented in the published EPD and modelling of current technology in waste management and timber recycling, and possible future scenarios.

The methodology for this study will be calculated in Simapro software using "IPCC 2013 GWP 100a version 1.03". This is a single-issue methodology; it will calculate only the global warming potential of the waste management process and modelled comparison processes in kg CO_2 equivalents. This is the updated version of the recommended midpoint impact assessment by the European Commission Joint Research Council (Manfredi, 2016)

This LCA study follows the ISO 14040/44 methodology (ISO, 2006a, 2006b). This standard includes the goal, definition, and scope of the life cycle assessment.

3.2. Functional Unit

The functional unit in this study will be $1m^3$ dimensioned timber in spruce.

The density of dried construction timber is 467 kg/m^3 at a relative moisture content of 17% (Gausdal-Treindustrier, 2021). Other products reported density vary but the respective mass per unit volume adjustments will be made to make results comparable. This will be reflected in Simapro modelling by spruce timber products kiln-dried to a relative moisture content of less than 20% within the Ecoinvent v3,6 database.

3.3 System Boundaries

The system boundaries for this study will be from cradle to grave, and then from cradle to gate (when modelling a circular product).

The initial modelling will reflect the processes involved with producing, using and disposing of $1m^3$ dimensioned timber, including energy recovery from municipal incineration.

To create a model for a circular timber product, the system boundaries will be shifted from cradle-to-grave, to cradle-to-gate with cut-off after C4. In this case, the gate being source material for remanufacture, or direct re-use of solid timber products.

The geographical boundary will be Norway.

The figure below (fig. 4) gives an outline of the unit processes involved with the production, use and disposal of $1m^3$ dimensioned timber contained within the system boundary, the linear model. This process flow chart is created from data from the EPD for the Gausdal Høvellast product and is representative for other dimensioned timber. For laminated timber, CLT, Limtre (Glulam) and K-Bjelke (laminated joists), production will also include the gluing and pressing process contained within the same system boundary.

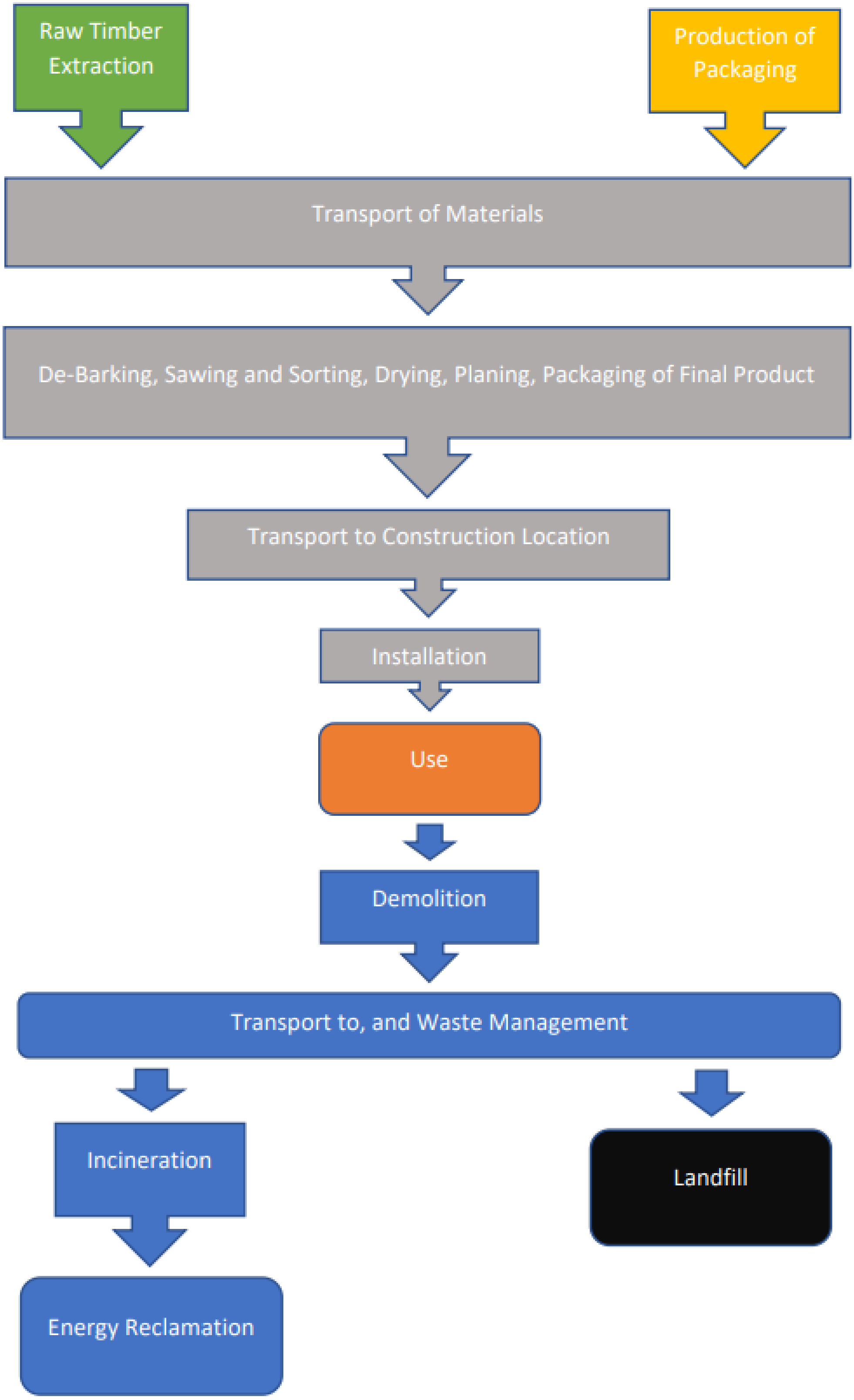

Figure 4 - Unit Process Flow Chart

3.4 Life-cycle Phases

The phases for the LCA of a construction product are as follows; Production (A1-A3), Construction (A4 & A5), Use (B1-B7), Demolition, Waste transport, Waste Treatment, Disposal (C1-C4) and Effects beyond the system boundary, re-use, recovery, recycling potentials (D). (NS-EN 15978)

Table 1 - Life Cycle Definition

Life-cycle phase	Data collected for this study
A1-A3	Raw material extraction and Production emissions taken from EPD
A4	Transport to site estimation taken from EPD
A5	Installation emissions and release of carbon from packaging as estimated in EPD
B1 - B7	Use phase emissions not included, assumed maintenance and upkeep emissions are negligible
C1	Demolition, emissions taken from EPD
C2	Transport from site to waste management, taken from EPD
C3 - C4	Emissions modelled in Simapro with ecoinvent v3.6 entries adapted with raw data collected from Ragn- Sells. Various scenarios modelled, with varying outputs to product system. Modelling cut-off at C4.
D	Possible products for re-use, recycling and energy recovery. Emissions and data taken from modelled scenarios and compared with Gausdal EPD and Sørlam EPD data (see Discussion)

Table 1 summarises the life-cycle phases and data sources for the products considered in this study.

3.4. Data Collection, Inventory Analysis and Impact Assessment

Data collection was carried out in three stages. Firstly, a database of Norwegian solid timber products which reported EPD data for life-cycle phases C and D was compiled. This database was then reduced to eight comparable products according to four criteria. This provided the eight products taken forward to analysis and scenario modelling. Second, primary data was collected from the Norwegian waste management industry. Third, Simapro software was used to model the primary data collected. Thus, providing input data for life-cycle phases C & D and the opportunity to model alternative waste management scenarios for the database products. This data allows GWP results to be calculated for the current practices and technologies in use in the timber industry. Further, results for possible circular models of those technologies and practices can also be calculated.

3.4.1 Data collection; Database of Untreated Norwegian Timber Products with “end-of-life" data.

Source material for the database of relevant EPDs for solid dimensioned timber products was found via EPD-Norge. This is a database of published EPDs in Norway. The search term “heltre produkter” (solid timber products) was used. This search resulted in 94 available EPDS (as of date of compilation of the database – January 2022). The total available list of EPDs for solid timber products was narrowed down to a short list of 8 comparable products using four criteria. First, the product needed be a solid timber product consisting only of, or being produced from, a cut and planed solid timber board. The category of solid timber products from EPD-Norge was quite broad and included, for example, timber I-beams used in flooring where the web of the beam was of imported fibreboard. Also, roof trusses came under the same category, which had a functional unit of 1 truss. The variation in functional unit was too great as to be comparable and the source timber for the fibreboard unknown, so these and similar products were disregarded. Second, the EPD needed to report data for phases C1-C4 and D. Without this information modelling of waste scenarios would be irrelevant as there would be no comparison data available. Third, the EPD needed to fall within the system boundary. Only products from Norwegian sourced forestry were included. There is common practice in Norway to buy timber from Sweden when domestic production is down, where this was declared, those EPDs were also included as this is an accurate reflection of the Norwegian industry. Fourth, the product must be "ubehandlet", meaning unpainted, unvarnished and non-modified. Modified timber products made up a large part of the available EPDs. Whilst modifying timber, by heat-treating and impregnating or finishing with a coating, often extends the usable lifetime of a timber product, it complicates the waste management process. Currently, modified, painted or varnished timber is sent to landfill in Norway, or incinerated where possible. The recycling of modified timber products has not been standardised and "classification methods for different recovered wood categories have to be developed before one can expect that real business emerges on recovered modified wood in the EU" (Herajarvi, H et al.,2020). Two products were untreated and passed three criteria. However, they were trim and solid timber flooring both of which are commonly painted or varnished in their usable lifetime and so were not included in the database.

The database is made up of eight EPDs that pass all four criteria. These products can be used in a closed loop circular economy (where the product is re-used to perform the same function without processing). They are all commonly used in timber construction in Norway. Modelling the possible waste management of these products will give insight into the effect of circular economy on the timber industry. (Appendix A; Database)

All EPDs compiled for this study were found through EPD-Norge (EPD-Norway). The information contained within each EPD is considered as accurate and as up to date as the age of the EPD and the LCA on which it was based. The EPD used as an example below, Gausdal Høvellast, has relevance with primary data from 2019 and is considered valid through to 2026.

3.4.2. Data collection; Primary data from industry

Primary data for this study was collected through a site visit to Ragn-Sells in Moss municipality. The contact from the waste management industry was Per Johansen, plan and strategy manager at Ragn-Sells. Data was gathered through conversation and email interactions. This included emission data from Ragn-Sells' processes from 2020 activity, machines and production lines used. It was found that very little, less than 1% of solid timber products coming into the facility were re-used, the majority, 80%, of timber products went to energy recovery through incineration, the remaining 20% was sorted and made into woodchips. These woodchips were then shipped to Latvia for remanufacture as fibreboard. The chipping process used three machines, a wheel-loader, excavator and a chipping mill all running on diesel motors. Specific inputs and outputs can be found below under C3 and C4 analysis of the example product, Gausdal høvellast. Ragn-Sells is a company with 22 facilities spaced over Norway and northern Europe all using the same production line for waste wood treatment. Data from Ragn-Sells give some information on current practice and provides a clearer understanding of the timber recycling practices and technology currently in use in Norway.

3.4.3 Data Collection; Simapro software

Simapro software was selected as a data source and calculation tool for this study. Simapro is based on the ecoinvent database. This is a continuously updated database of unit processes, inputs, outputs and their environmental impacts. This study used Simapro version 9.1.0.11, with ecoinvent library v.3,6 as compiled in December 2019.

Initially Simapro was used to model the EPDs of available products. However, this modelling produced results that did not match the EPD information. The simulations showed only marginal reductions in emissions despite modelling closed loop recycling of the products. Another approach was taken to allow the inclusion of embodied carbon within the product. This resulted in data being taken directly from the eight available EPDs for life-cycle phases A1-C2. Simapro was used to model the waste management of the products, phases C3 and C4.

Within Simapro a waste scenario was created based on adapted entries to the ecoinvent database. A process for sorting and chipping returned wood was modelled with all ecoinvent data being adjusted for a Norwegian power mix, diesel consumption and steel production for the machinery. Primary data was used in combination with adapted ecoinvent database entries.

Closed loop recycling of the product was considered to give no emissions at waste management phase so this could be modelled by not including the outputs of the waste management scenario. Open loop recycling was modelled (100% woodchip for remanufacture), where the product is processed for remanufacture (chipped for export to Latvian Fibreboard production) and allocation adjusted to reflect the current practice as taken from primary data. Impact assessment was done by running calculations on a single impact methodology IPCC 2013 GWP 100a version 1.03. This was the same calculation used to produce EPD results so was comparable to the data retrieved from the relevant EPDs.

3.5. Inventory analysis and impact assessment process

Each product was analysed by life-cycle phase and data compiled for comparison. This process was a combination of data from the collected EPDs, primary data from industry or from simapro simulations. The scenario results were calculated by modelling the products with differing percentages of closed loop and open loop circular models. This process with reference to the example product, Gausdal Høvellast, are examined last.

3.6 Example product Gausdal Høvellast

The following is an example of the process employed to create the inventory for this study. This process was repeated for each of the EPDs compiled in the database. Here the focus is on Gausdal Høvellast.

3.7 A1-A3: Raw material extraction and production

Data for the production and extraction of raw timber is taken from the report of Norwegian forestry 2013. (Signe Kynding Borgen, 2013) This is a report undertaken as part of the Klimatre project, where data on common Norwegian forestry practices were collected to perform an LCA of the environmental impacts cradle to gate of the Norwegian forestry industry with raw production data from 2010. The system boundary for the study included averaged domestic seedling cultivation, through to the gate of the sawmill and timber product production gate. The study included all relevant data on building and maintenance of forest roads, terrain preparation, thinning of planted forest, and final harvesting and transport to industry. Functional Unit of the study was $1m^3$.

Data from production year 2019 for Gausdal sawmill was then combined with a calculated absorption of biological carbon in $1m^3$ of softwood timber of 732 kg CO_2 eqv. As shown in table 2.

Table 2 - GWP 100a data from Gausdal EPD A1-A3

Parameter	Unit	A1-A3
GWP	kg CO_2 eqv	-675

A4 and A5: Transport to site and installation emissions

The location of the Gausdal plant is within 75Km of the modelled waste management site. Within this radius are the towns of Lillehammer, Gjøvik, Hamar and Brumunddal. The transport to installation modelled in the EPD was that of 170km heavy goods vehicle (>32 tonne) and 30km with a lighter vehicle (12-32 tonne). This is an acceptable distance for a project within this geographical boundary.

Installation of the product was modelled to result in 1MJ of electrical energy used, plus the disposal and incineration of product packaging, as displayed in table 3.

Table 3 - GWP 100a data from Gausdal EPD A4, A5

Parameter	Unit	A4	A5
GWP	kg CO_2 eqv	9,47	3,77

C1 and C2: Demolition and transport to waste treatment

Data for demolition has been taken from the Gausdal EPD, again the estimated energy use was 1MJ. For transport to waste treatment, a normal work vehicle was modelled with an average distance to waste centre taken from a 2007 paper of 85km measured at 0,03 l/tkm. GWP emissions displayed in table 4.

Table 4 - GWP data from Gausdal EPD C1, C2

Parameter	Unit	C1	C2
GWP	kg CO_2 eqv	0,00881	4,99

C3 and C4: Waste treatment and waste disposal

Raw data from Ragn-Sells waste treatment centre was collected through interview and via a site visit to Ragn-sells waste management facility in Moss. The company uses a similar infrastructure at all sites in Norway. A three-stage production line is used to produce woodchips from returned timber. The line consists of a wheel loader and an excavator servicing a semi static diesel powered woodchipper. The chipper is powered by a 1000HP diesel motor which also provides power to an integrated electromagnet in the mill which removes unwanted metal (fastenings and scrap) from the chipped timber. The production line is calculated to burn 1L diesel per tonne woodchips produced (with variations for weight due to moisture content 1 tonne woodchips is equivalent to $5m^3$). Energy content for 1L diesel fuel burned in construction machinery is 38MJ. Therefore, the production line uses 0,003L/kg * 38 MJ = 0,114 MJ per kg woodchips. This was used as the energy input when modelling in Simapro. The reliability of this data is considered as robust and as up to date as the date of submission of this study. Figure 5 shows a diagram of the GWP emissions from each process involved in the waste scenario as modelled in Simapro.

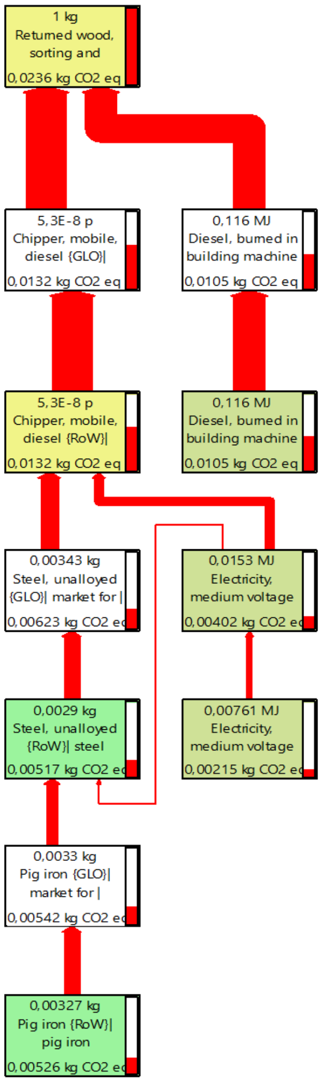

Figure 5 – GWP emissions- process network diagram for Ragn-Sells woodchip production

Table 5 shows GWP emissions when modelling 100% of returned timber going to wood chip production at a Ragn Sells facility, using single issue GWP100a methodology. This model assumes that the woodchips would then be used as a source material for remanufacture, therefore no transport after woodchip production is included. This transport would fall outside of the system boundary as it would be part of the next unit process, for example, fibreboard production.

Table 5- GWP data from Simapro model of Ragn-Sells woodchip process

Parameter	Unit	C3 and C4

GWP	kg CO_2 eqv	0,0236

The data from Gausdal EPD was also used as a comparative data set. Note that the emissions for C3 are significantly higher due to the incineration and therefore release of bound carbon dioxide from the returned timber, as shown in table 6.

Table 6 - GWP data from Gausdal EPD C3 and C4 combined

Parameter	**Unit**	**C3 and C4**
GWP	Kg CO_2 eqv	739,0367

D: Effects beyond the system boundary, re-use, recovery, recycling potentials

Data for phase D was taken from the Gausdal EPD and modelled for comparison according to different waste treatment and waste management scenarios. The calculation of the GWP impact is complicated by the fact that this study is modelling a product which includes embodied carbon. Carbon that has been absorbed whilst the trees are growing in the forest, then released when returned timber is burnt to recover energy. This study will focus on GWP impact with a cut-off after phase C4. Phase D, possible inputs, results, and complications will be addressed in the Discussion.

3.8 Scenario Modelling

This section explains the scenario modelling process with reference to the example product, Gausdal Høvellast. This same process and and compilation of results was repeated for each of the eight included timber products included in this study.

The Results table 7 shows the four scenarios modelled for this study. The totals shown at the bottom of each column represent the amount of kg CO_2 equivalents released in a process stream before the consideration of possible benefits outside the system boundary. The fifth scenario is displayed to give oversight of the calculations made to arrive at the four modelled scenarios.

As can be seen in table 7, GWP emissions for product phases A1 through to C2 are identical and taken from the relevant EPD, in table 7 the example product Gausdal Høvellast. To calculate GWP for phases C3 & C4 of Current Technology (CT) and Optimised Current Technology (OCT) representative and alternative percentages of the emissions per kg were taken from the scenario of 100% woodchip production. Emissions for C3&C4 of this scenario were taken from the simapro model (fig. 5), 0.0236 kg CO_2eqv per kg, and adjusted for mass per m^3 (For Gausdal Høvellast, 0.0236*467kg = 11,0212 kg CO_2eqv per m^3). For each product the mass was adjusted to allow for comparability and variation in product density.

3.8.1 EPD scenario

This scenario is represented in the orange column in table 7. It is the calculation of the GWP of the Gausdal dimensioned timber EPD cut-off at C4. This results in the exclusion of possible reductions in GWP emissions from energy recovery from waste incineration.

3.8.2 Current technology Scenario

This scenario is shown in blue in table 7. This scenario is a model of “business as usual” for the process stream of a solid timber product in Norway.

This scenario reflects the current use of infrastructure available, where 20% of returned timber is chipped and then sold for remanufacture, the remaining 80% is incinerated through municipal waste channels (NEG- Norwegian Energy Recovery). The GWP result is taken from the sum of 20% “woodchips for remanufacture” and 80% “EPD” scenarios.

3.9 Optimised Current Technology (OCT) and Circular Scenarios

OCT (yellow in table 7) models a stated intention from Ragn Sells to increase the re-use of timber products significantly by 2024. When a product is re-used in the model then there is no GWP emissions from phases C3 and C4. Transport from a theoretical demolition site to a waste management facility is accounted for in C2 and further handling or sorting would be outside of the system boundary. The transport and handling would be part of the material sourcing process for the next product cycle.

OCT models 10% direct re-use of returned dimensioned timber, 20% woodchip production for remanufacture and 70% incineration (EPD).

Circular (green in table 7) is a model of a circular timber industry in Norway. No waste management or waste disposal activities contribute to GWP of the timber product. This is the optimal outcome, where all timber materials are cycled back into re-use without waste treatment and processing after use. It is idealised and unlikely to be wholly achievable as it relies on no product damage or waste through use, demolition and transport. It is included here to show comparison with GWP reductions in other models.

4. Results

This section presents the results from the LCIA modelling and the comparisons in possible emission reduction in different modelled scenarios. Results from the example product, table 7, will be presented to demonstrate how results were collected for each modelled scenario. Table 8 and figure 6 show the results of all eight products in comparison. This is the source for this study’s main findings. Finally, results for phase D (table 9 & fig. 7) and Limtre, Sørlam (table 10) have been included for reference in the discussion.

4.1. Gausdal Høvellast Results

Table 7 shows the results from the modelling of the example product, Gausdal Høvellast.

Table 7 - Scenario Results Summary- Gausdal høvellast

	EPD		Circular	Current Tech	Optimised current tech (OCT)
GWP kgCO2 eqv	100% Incineration	100% Woodchip production for remanufacture	100% Solid timber re-use	20% Woodchips for remanufacture, 80% Incineration	10% Re-use, 20% woodchips, 70% Incineration
A1-A3	-675	-675	-675	-675	-675
A4	9,47	9,47	9,47	9,47	9,47
A5	3,77	3,77	3,77	3,77	3,77
C1	0,00881	0,00881	0,00881	0,00881	0,00881
C2	4,99	4,99	4,99	4,99	4,99
C3-C4	739,0367	11,0212	0	593,4336	519,52993
SUM	82,28	-645,74	-656,76	-63,33	-137,23

4.2. Results Comparison.

The table 8 below shows a summary of the scenario results from all eight products across the four modelled scenarios. These are the GWP of each product with cut-off after C4. Note only Limtre, Sørlam has an anomalous result, showing a positive net carbon emission from the current technology scenario.

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Table 8 - Results Comparison

GWP kgCO2e	Høvellast, Moelven	Høvellast, G3	Konstrv. Inntre	K-Bjelken	CLT	Limtre, Sørlam	Limtre, Proj. Moelven	Limtre, Std, Moelven
EPD	107,99	82,28	78,38	127,76	106,67	168,44	92,72	106
CT	-51,05	-63,33	-67,02	-11,64	-30,72	9,86	-44,46	-31,38
OCT	-131,45	-137,23	-140,82	-82,34	-100,42	-70,44	-114,16	-101,18
Circular	-696,05	-656,76	-659,65	-579,26	-590,34	-634,6	-604,28	-592

Figure 6 is a graph of the results summary. The graph shows that the current technology scenario has lower GWP than reported in the collected EPD. Results from modelling a closed loop timber product, circular scenario, has significantly lower emissions than all other models.

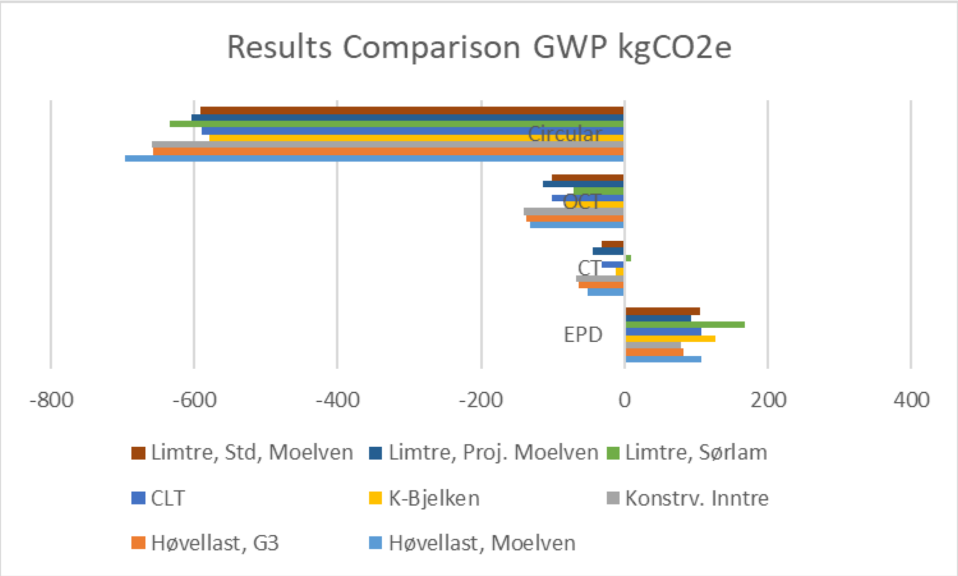

Figure 6 - Results Comparison GWP kgCO2e

Figure 6 shows the main findings of the study. Namely that the model of current technology results in far lower emissions than reported in the products' respective EPDs. Secondly, that a small increase (10%) in the adoption of re-use (closed loop circular economy) of all the timber products assessed in this study resulted in >200% reduction in

GWP for all products in comparison to the current technology model. (Average percentage gains [OCT vs CT] calculated from table 8 = 387% of GWP, lowest individual product gain over CT = 210%)

4.3. Results for Phase D

Table 9 and figure 7 show comparative results for phase D for all products in three of the modelled scenarios; EPD, CT and OCT.

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Table 9 – Results phase D

kgCO2e	Høvellast Moelven	Høvellast G3	Konstrv. Inntre	K-Bjelken	CLT	Limtre Sørlam	Limtre Proj. Moelven	Limtre Std Moelven
EPD	-34	-31	-40,1	-30	-30,3	-35,3	-30,4	-30,7
CT	-78,25	-88,13	-99,1	-35,64	-54,96	-18,38	-68,78	-55,94
OCT	-155,25	-158,93	-168,89	-103,34	-121,63	-95,15	-135,44	-122,67

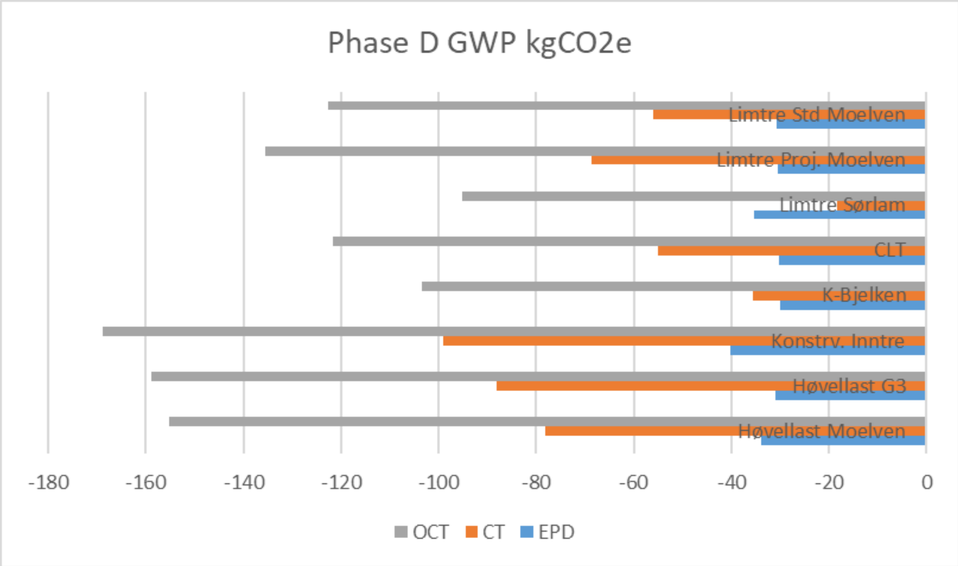

Figure 7 - Phase D GWP kgCO2e

4.4. Results for Limtre, Sørlam

Table 10 - Results Limtre, Sørlam

Limtre, Sørlam	EPD		Circular (Optimal)	Current Tech	Optimised current tech (OCT)
GWP kg CO2 eqv	100% Incineration	100% Woodchip production for remanufacture	100% Solid timber re-use	20% Woodchips for remanufacture, 80% Incineration	10% Re-use, 20% woodchips, 70% Incineration
A1-A3	-659	-659	-659	-659	-659
A4	11,2	11,2	11,2	11,2	11,2
A5	8,06	8,06	8,06	8,06	8,06
C1	0,00881	0,00881	0,00881	0,00881	0,00881
C2	5,13	5,13	5,13	5,13	5,13
C3-C4	803,04444	10,148	0	644,47	564,16
SUM	168,44	-624,45	-634,60	9,86	-70,44

5.0 Discussion

In this section the main findings of this study will be discussed and the implications these findings have on the problem statement and purpose of the study. Whether it is possible to compare the analysed products will be discussed and the implications on our findings. Discussion of secondary issues concerning phase D calculation, transport and possible hinderances to a circular timber industry will be considered in light of the results. Lastly, we will consider limitations of the study and possible future work.

5.1. Main findings

There are two main findings from the results. First, the results from modelling current practice and technology (CT) have significantly lower emissions than reported in the EPDs of all products. Second, an adaptation of current practice to a 10% circular economy for the timber products results in more than a 200% reduction in GWP for the products in the study.

The implications of these findings for the purpose of this study are that we can inform industry that introducing circular economy to these products can result in reduced GWP emissions. The question of whether significant reductions in emissions can be made by optimising current technologies and practices can be answered. By introducing a small percentage of re-use of the analysed products the Norwegian timber industry might achieve a reduction of more than 200% of GWP emissions from current practice of waste management of these products (table 8).

The limitations of having so few available EPDs for timber products with end-of-life data are that we make these conclusions based on only eight products. These products are sold in large quantities in Norway. However, it would be inaccurate to extrapolate these results to apply to the entire Norwegian timber industry and its many thousands of different products. Results from modelling may vary significantly when different timber products are considered. Further work is required to make a generalised assessment on the entire industry. EPDs are a requirement for inclusion in BREEAM projects, the total number of EPDs is increasing. In the future a general statement may be possible.

5.2. Comparison of products

Comparisons have been drawn between products with different production processes. Three products are harvested, dried, sawn, and planed. The others, Limtre, CLT and K-bjelke are also glued and pressed to form laminated timber elements. Data from EPDs was not adapted for A1-C2. This is shown in the results, figure 6, where the glued and laminated products have slightly higher emissions and therefore less possible reductions in GWP in the modelled scenarios. However, similar reductions in emissions are achieved through the modelled changes in practice. For seven of the eight products current practice of a partially open loop circular economy (CT scenario) results in a greater net reduction in GWP than incineration. The glued laminated products can be compared with the dimensioned timber in terms of gains made in GWP due to changes in practice.

There is an anomaly in the results. Limtre from Sørlaminering produces results show higher GWP from incineration (EPD scenario), the same trend in reduction of emissions is followed through the modelling as other products considered by this study. This situation arises from a difference in calculation of the net emissions produced through incineration. It is significantly higher than all other products in the study. The product's modelling results for each life-cycle phase is shown in table 10.

When these results are compared to that of the Gausdal EPD, table 7, it can be seen that the amount of GWP for phase C4 has been calculated differently. Approximately the same reductions in GWP are achieved through modelling so the anomaly is not seen to undermine the findings of the study. This could be an example of the difficulty in calculating the release or retention of embodied carbon in a product. We are satisfied that these results are comparable, but it is not known whether these results can be generalised across the entire timber industry. Further work would need to be done to assess whether similar reductions can be achieved with more complicated products, for example, I-beam floor joists as described in the data collection.

5.3. Phase D

The calculation for a circular product which has embodied carbon complicates the models. This is problem is well known and a process for accounting and allocating for embodied carbon in timber products is under development. Here, we will examine the implications on our results and ultimately why phase D was not included in the modelling. The system boundary was cut-off after phase C4 as D includes the calculation of embodied (also referred to as sequestered) carbon in kg CO2 equivalents. This calculation is complicated and has no standardised method for analysis as set out in PCR for timber products.

Embodied and sequestered carbon is a grouped term referring to all greenhouse gasses absorbed by timber products during growth and released by product development and disposal. Timber products are often considered net negative carbon products as they take up kg CO_2 equivalents in production and store that carbon until they are incinerated or breakdown in nature. When decomposing in nature or landfill, even then only a small amount of carbon is released, though methane can be produced which to some is a positive as it can be used as a biogas source. Similarly, producers of CO_2 view natural release of CO_2 as a positive as it is a source for natural biogas (ISE, 2021, website). Due to this muddled picture where the release of embodied carbon can be viewed as both a positive and a negative by different industries, the European commission has been developing a more accurate tool for the overall calculation of the emissions from a product. The PEF (Product Environmental Footprint) tool is still in a transitional phase and will be set in PCR by the end of 2024 (Manfredi, S et al, 2012, website). Currently the use of embodied carbon calculation can be adapted to make a product, or process stream, appear better for the environment, for example net carbon gains from the release of carbon through incineration and "green" energy recovery. In the case of Norway this would be energy production then export to replace energy produced from petrochemicals. The PEF tool is a method that will hopefully nullify this practice.

In this study, by cut-off before phase D and modelling a circular product, the embodied carbon in the timber product has been considered whilst not needing to account for complicated gains or losses of carbon through energy recovery.

Table 9 and figure 7 show the results from this study's models for phase D. The EPD scenario includes energy recovery from burning biomass, this makes the product a net negative carbon product. This seems counter intuitive as the embodied carbon contained within the product has been released into the environment. The phase D results for all other modelled scenarios result in at least double the amount of embodied carbon being preserved, even current technology where 80% of the original product is incinerated. There is one anomaly, Limtre from Sørlam, where the EPD out-performs the model of current technology. This result would suggest that it produces less carbon to incinerate the product than to recycle it. However, if just 10% of this product is re-used as shown in OCT, the reduction in GWP of nearly 270%.

Results for products with embodied carbon are difficult to model. Within Simapro there are often mass imbalances and default settings in generic waste treatment processes that result in the benefits from preserving embodied carbon not being calculated. In consultation with Simapro they advised to look to the new PEF calculations. Again, this method will not be official until 2024, therefore results for this paper include a cut-off of the system boundary after C4. Future work would be to reassess the phase D results after the final introduction of the PEF format.

5.4. Transport

Data collection from Ragn Sells showed that current practice for remanufacture is to transport woodchips by boat and heavy road vehicle to Latvia for fibreboard production. This is an environmentally positive process as it results in a net reduction of GWP emissions. However, to reduce the net footprint of this timber product and to keep the entire cycle within the geographical boundary of the study, it would be optimal that the woodchips were transported to a Norwegian fibreboard producer. An example would be the Hunton factory in Gjøvik which is located <100km from the Gausdal facility. Not only would transport, and the connected emissions, be reduced but the manufacture of the fibreboard would be under the Norwegian power supply which is approximately 99% renewable (app.electricitymap.org). This study has shown that small changes to current practice within current technological limits can have significant effects on GWP output of a timber product in Norway. Transport, and specifically modes of transport, can have significant consequences for the footprint of a product. This could be an opportunity to build industrial symbiosis between waste treatment (Ragn Sells) and use of that product as source material for fibreboard production (Hunton). This could result in reduced GWP output as the production of raw materials, extraction, use, demolition, transport, waste treatment and remanufacture of a timber product could be contained within a 100km radius without any need for new infrastructure.

5.5. Politics, legislation, and regulation

Here we will examine the possible difficulties of the Norwegian timber industry adopting a 10% increase in re-used timber products and the implications for our main findings.

As of specific regulations regarding recyclability of timber, there is little information. The Norwegian government have adapted its regulations as of June 2022 to include a circular approach to new buildings, but this will probably not be relevant until these buildings will be disassembled. In Norway, it is required to use timber with the classification of minimum C24 for load bearing structures, and currently there is uncertainty regarding the possibility of reusing reclaimed structural components like rafters and glue-laminated beams. The EU and UN are introducing laws and regulations in its member states, but specific regulations probably need to be nationally adopted to comply with the situation of that country.

5.6. Deterioration of timber over time

Further hinderances to the increased practice of the re-use of timber products include the issues regarding the decay of wood that may create the need to document the reclaiming, storage, and transport process before and after demolition or refurbishment of a timber product. Especially if the reclaimed timber is intended to become a structural component. As shown in section 2.3.2. timber as a material is susceptible to rot and deterioration over time, introductions of new building standards which incorporate re-used timber in a non-structural role could become a significant obstacle to a circular timber product. For example, if a treatment of the pre-used timber was required, or extra transport to a treatment facility, the resulting emissions could affect the results of this study.

6.0 Limitations and Future work

6.1 Data and Sensitivity analysis

This study is based on data collected from EPDs, first hand raw data from Industry and adaptions of generic processes within the Ecoinvent database as described in the methodology. Conclusions drawn from results from this data are limited to the data available. A single EPD has been used to represent a whole branch of the timber industry in Norway. This EPD though appearing to be up to date and of high quality, is inherently vulnerable to the decisions made by the consultant performing the LCA and the conclusions drawn from that study when writing the EPD. Similarly, the data from Industry, though accurate and up to date, is relevant to one specific actor within localised geographical boundaries, namely Ragn Sells waste facilities. The data drawn from Ecoinvent is more generalised and has been adapted to fit the geographical boundaries of the study. However, European wide averages have been used where no other more accurate data was available. To ensure the validity and relevance of these results, future work would need to be done to perform both a data quality analysis and sensitivity analysis of the data used. This would establish whether the factors being adjusted in the modelling in this paper are those producing the results reported, most importantly that the results are replicable and reliable.

6.2 Future Work

This study has focused on the end-of-life phases of timber products in Norway. Future work could be done to assess the possible improvements that could be made to the raw material growth and extraction within Norway. When modelling the forestry industry, ecoinvent data from Sweden was adapted to mirror Norwegian practices and this consistently resulted in lower GWP emissions in analysis than those used in the Gausdal EPD. The EPD was based on a paper from 2013 which assessed the footprint of the forestry industry in Norway (Timmerman, 2013) This data was reliable though could be outdated as it relies on FSC status which is updated every two years.

Further investigation could also be done into the adjustment of practices currently used in industry. Timber structures in Norway are commonly demolished using an excavator with a hydraulic claw to shred the structure. More careful demolition with a focus on maintaining the integrity of timber elements with a view to re-use of those products could lead to a larger percentage of directly re-used material. Future work could include an assessment of the economic effects of delicate demolition versus carbon emission reduction within a circular timber industry.

7.0 Conclusion

This paper has shown that the Norwegian timber industry has an opportunity to lead the way on reducing climate gas emissions. Circular economics is a useful, effective, and intuitive solution to achieving a reduction in carbon emissions. Currently, Norway has the infrastructure to improve its carbon footprint. What is most environmentally advantageous is to adapt practices in line with circular economics to optimise this reduction in GWP. From the results of this study, it is plausible that current technology and practice in fact results in lower GWP than is reported in the EPDs of the relevant products. This reflects the fact that some concepts of circular economics are already in use; 20% of timber is being remanufactured into other timber building products. If that uptake of circular economics was expanded to include a 10% increase in re-use of dimensioned timber, a larger reduction in GWP emissions could be achieved in comparison to current practices without the need for investment in new infrastructure.

This study has shown that small changes in current practices can have significant effects on carbon emissions from products within the Norwegian timber industry. What needs to be recognised and was discussed above, is that small changes to any additional treatment process, or heavy goods vehicle transport may also have significant impacts on the emissions from those products. A positive aim would be change at the system level, where circular products, especially those with embodied carbon, are used as many times as possible and for as long as possible. Future practice within the industry would need to avoid the detrimental effects of long-distance transportation and industrial processing if we are to reach the UN sustainability goals. Future work could be done to clear any hinderance to the adoption of circular economics in the timber industry. Political, legal, and economic solutions need to be found to incentivise the adoption of circular economic practices that have been shown in this study to have a positive effect on the environment.

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***Appendixes*:**

Product	Title/ Reference	System Boundary	Geo-scope	LCA data source	LCIA Method and indicators	Major Findings	Notes	Inventory data source	A1-A3	A4	A5	B	C1	C2	C3 & C4	D
								Inventory data source	A1-A3	A4	A5	B	C1	C2	C3 & C4	D
Product	Date of compilation Jan.22							Inventory data source	GWP						GWP kgCO_2-eqv	
Limtre bjelke	Standard limtre bjelke, Moelven, NEPD-1576-605	Cradle to grave, A1-C4 and D	Norway	EPD, Primary Data,	EPD 2018	Following found using EPD-Norge Digi. 1143 files online. Classification "tre", country/ region "Norge" - 54 av 1143 examined, many relevant products (eg Kebony) valid only until close of 2021.	Information on the recovery of energy from burning biomass and exporting the energy produced, was obtained from "statistikk sentralbyrå (2019)". Lifetime of 60years. FU=1m^3, Mass/m3 = 470kg gran	Ecoinvent v3.4 and primary data for skogbruk (2010) and production (A3) in 2016	-608	10,3	1,05	X	8.68E-3	4,64E+00	C3=698 , C4=0.0056	-30,7
Limtre bjelke	Prosjekt Limtre, Moelven, NEPD-1577-605	A1-C4 and D	Norway	EPD, Primary Data,	EPD 2018		Very similar EPD to the standard Limtrebjelke. FU 1m3. Note difference in installation emissions. Mass/m3=470kg	As above	-616	7.07E00	8,68E-03	X	8.68E-3	4.63E00	C3=697 , C4=0.0056	-30,4
Limtre bjelke	Limtre bjelke, NEPD-2531-1274-NO, Sørlaminering AS	A1-C4 and D	Norway	EPD, Primary Data,	ReCiPe 2008	valid through 2025	Different limtre producer than Moelven, FU=1m3, Calculated as a less carbon heavy product. Mass/m3=430kg	Primary data from 2018, Skurlast from EPD, Ecoinvent v3,5	-659,00	1.12E1	8,06	X	8.81E-3	5.13E00	C3=803 , C4=0.0444	-35,3
Høvellast	NEPD-2748-1441-NO, G3 Gausdal Tre, Høvellast av gran	A1-C4 and D	Norway	EPD, Primary Data,	EPD 2018	Dimensioned timber, FU1m3 spruce	Burning of biomass in C3 C4 and D, FU 1m3, 467kg/m3	Raw material from 2013 paper. Primary data for production from 2019, otherwise all upstream generic data from ecoinvent v3,5	-675	9,47	3,77	X	8,81E-03	4,99	C3=739 , C4=0.0367	-31
	NEPD-3282-1918, Inntre Kjeldstad, Konstruksjonvirke av gran	A1-A5, C1-C4, D	Norway	EPD, Primary Data,	EPD 2018	Dimensioned timber, FU1m3, 467kg/m3 spruce	Burning of biomass in C3 C4 and D	Raw material extraction from 2013 paper, skurrlast adapted from sweden, raw data from production in Norway in 2019, otherwise ecoinvent v.3,7	-675	4,43	5,9	X	6,63E-03	5,01	C3=738, C4=3,72E-2	-40,1
	NEPD-2547-1284, Moelven, Høvellast av gran eller furu	A1-A5, C1-C4, D	Norway	EPD, Primary Data,	EPD 2018	Dimensioned timber, u 20% water content, FU1m3 spruce 375kg/m3 (or pine 435 kg/m3)		Production raw data from 2018, extraction based on 2013 paper, energy recovery from national office of statistics.	-723	13,7	7,81	X	8,81E-03	5,43	C3=804, C4=4,00E-2	-34
CLT	NEPD-2042-902, Krysslimt tre, Splitkon AS, Cross laminated timber building elements	A1-A5, C1-C4, D	Norway	EPD, Primary Data,	EPD 2018	Clt Elements, FU 1m3, 425kg/m3		Raw material extraction data from NO suppliers, otherwise relevant EPD and ecoinvent v3,4, plus Østfoldforskning database	-597	2,89	2,39E-01	X	8,38E-03	3,52	C3=697, C4=1,73E-02	-30,3
K-bjelke	NEPD-1384-455-NO, K-Bjelken in spruce, Kjeldestad Trelast As	A1-C4 and D	Norway	EPD, Primary Data,	EPD 2018	FU 1m3 laminated and glued beams and studs of spruce designed to give better structural performance than dimensioned timber. Mass= 425 kg/m3	Recovery of energy through incineration in C3-4 and D	Primary data for production both of beam and glue. Otherwise data generic ecoinvent v3,3	-600	10,7	5,39	X	9,88E-03	4,64	C3=707 , C4=0,0193	-30