CARBON FOOTPRINT OF THERMALLY MODIFIED TIMBER AND PLANED PRODUCTS

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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In this work, the carbon footprint [kg CO_2 eq/m^3] of the thermally modified wood and planed products of Lunawood was researched. Cradle-to-grave approach from harvesting up to disposal was used in selected market areas, which were Germany, the UK, the USA and South Africa. End-user phase was also taken into account in both interior and exterior cladding by comparing different lifetimes and areas covered. The emissions of by-products from planing and the emissions related to the sold bioenergy were also taken into account.

The carbon footprint of thermally modified wood products was compared with the carbon footprint of tropical hardwood and the products of closest competitors of Lunawood. Carbon dioxide emissions from recycling are estimated by how much wood is recycled with the selected market areas and how much wood chips are made from the recycled wood. The carbon dioxide emissions from the treatment of municipal solid waste sent to landfill were used in the calculation as emissions from the disposal phase.

Based on this research, it can be said that the Finnish thermally modified wood manufacturer's thermally modified wood binds more carbon dioxide from the air than 1 cubic meter (m^3) of the manufactured product emits along it's life cycle. According to this study the cradle-to-grave carbon footprint of the Finnish thermally modified wood manufacturer's timber and planed are 225 – 396 kg CO2 eq/m^3 and 247 – 419 kg CO2 eq/m^3, respectively. Carbon footprint of tropical hardwoods with gate-to-gate approach Light Red Meranti and Dark Red Meranti were 211 and 337 kg CO2 eq/m^3, respectively (Ratnasingam et al., 2015). In that study of Ratnasingam et al. (2015), emissions caused by harvesting, transport, recycling, disposal were not taken into account in their carbon footprint calculation of Light Red Meranti and Dark Red Meranti.

TIIVISTELMÄ

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Lämpökäsitellyn sahatavaran ja höylätyn tuotteen hiilijalanjälki

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Tässä työssä selvitettiin erään suomalaisen lämpöpuuvalmistajan, Lunawoodin, lämpöpuun ja höylätyn lämpöpuun hiilijalanjälki [kg CO_2 eq/m^3] raaka-aineen hankinnasta aina loppukäytön kautta kierrätykseen ja lopulta lämpöpuun hävittämiseen (cradle-to-grave) valikoiduilla markkina-alueilla, jotka ovat Saksa, Iso-Britannia, USA ja Etelä-Afrikka. Myös käytön aikaiset hiilidioksidipäästöt otettiin huomioon niin sisä- kuin ulkoverhoilussa eri käyttöikiä ja neliöitä vertaamalla. Työssä allokoitiin höyläyksessä syntyvän lämpöpuupurun päästöjen vaikutus ja myytyyn bioenergiaan liittyvät päästöt.

Lämpöpuun hiilijalanjälkeä verrattiin troppisen kovapuun ja suomalaisen lämpöpuuvalmistajan lähimpien kilpailijoiden hiilijalanjälkeen. Kierrätyksen hiilidioksidipäästöjä arvioitiin, kuinka paljon valituilla markkina-alueilla kierrätetään puuta ja kuinka paljon kierrätetystä puusta valmistetaan haketta. Kaatopaikalle vietävän kunnallisen kiinteän jätteen käsittelyn hiilidioksidipäästöjä käytettiin laskennassa loppusijoitusvaiheen päästöinä.

Tämän tutkimuksen perusteella voidaan sanoa, että suomalaisen lämpöpuuvalmistajan tuotteet sitovat ilmasta enemmän hiilidioksidia kuin 1 kuutiometristä (m3) valmistettua tuotetta vapautuu elinkaarensa aikana. Tämän tutkimuksen mukaan suomalaisen lämpöpuuvalmistajan lämpöpuun ja höylätyn puun kehdosta hautaan hiilijalanjälki on 225 – 396 kg CO2 ekv/m^3 ja 247 – 419 kg CO2 ekv/m^3. Trooppisten lehtipuiden hiilijalanjälki portilta portille -lähestymistapalla Light Red Meranti ja Dark Red Meranti olivat 211 ja 337 kg CO2 ekv/m^3 (Ratnasingam et al., 2015). Tuossa tutkimuksessa korjuun, kuljetuksen, kierrätyksen ja hävittämisen aiheuttamia päästöjä ei huomioitu lainkaan.

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Työni on vaihtunut, mutta saan olla joka päivä tekemässä suomalaiselle lämpöpuuta valmistelevalle yrityksellä vastuullisuuteen liittyviä työtehtäviä. Tästä yrityksestä löytyi myös mielenkiintoinen DI-työn aihe: lämpöpuun hiilijalanjäljen laskeminen, jossa arvioitaisiin käytön aikaiset hiilidioksidipäästöt. Tämän DI-työn tavoitteena on ollut laskea lämpöpuulle hiilijalanjälki kehdosta hautaan.

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Johanna

SYMBOLS AND ABBREVIATIONS

Symbols

kg	kilogram
m^3	volume
CO_2	carbon dioxide
m^2	square meter

Abbreviations

EPD	Environmental Product Declaration
ITTO	International Tropical Timber Organization
LCA	Life Cycle Assessment
FSC	Forest Stewardship Council
PEFC	Programme for the Endorsement of Forest Certification
GWP	Global warming potential
UK	United Kingdom
USA	the Unites States
SDGs	UN Sustainable Development Goals
BREEAM	The world'sleading science-based suite of validation and certification systems for a sustainable built environment
LEED	Leadership in Energy and Environment Design
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
CML	impact assessment method to calculate global warming potential
LPG	Liquid Petroleum Gas

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1 Introduction

Corporate responsibility is at the forefront of strategy and strategic innovation. Sustainability is also not seen any more as environmental sustainability, but now companies want to be brought up what social sustainability and governance mean for them and their value chain. As environmental awareness increased, companies highlight more and more how environmentally friendly, ecological or sustainable their products are.

Different companies are increasingly presenting life cycle assessments of their products or services to consumers. The limitations of the calculation vary according to the system boundaries. The Finnish Sawmill Industries has made Environmental Product Declaration (EPD) for products of the sawmill industry and their further processed timber products in accordance with EN15804 + A1 (RTS_124_21). After June 2022 an updated version of the same standard, EN15804 + A2 will be used. It includes several indicators to describe the environmental impact of a product. The life cycle assessment of Finnish sawn and planed timber products from cradle-to-gate is presented in this EPD including presentation of limitations in the description.

In this EPD by Finnish Sawmill Industries an average sawn product and planed timber are used. This EPD does not include further processing such as surface treatment. The calculation takes into account forest management and supply of raw material from the forest (module A1), the transport of logs and semi-finished sawn timber to the sawmill (module A2) and sawmilling, kiln drying and planing (module A3). In relation to energy use, the EPD has looked at fuels and lubricants for used manufacturing equipment and working machinery, the use of water and the packaging materials of finished products. The energy made from the sawmilling by-products and used by the sawmills themselves have been allocated to the products. Module 4 takes into account transport to the site. The EPD does not take into account the environmental impacts of manufacturing of machinery, equipment or infrastructure but it includes their energy needs. The environmental impact of the demolition phase of the building includes transport, chipping and energy use. Supplementary information beyond the life cycle impacts have been assessed for Module D. The EPD notes that the lifecycle effects of spruce and pine are similar, but there are differences in moisture, density and biogenic carbon in wood species. (RTS_124_21).

Oy Lunawood Ltd has made such an EPD which was updated to correspond to the standard updated format EN15804 + A2. This is limited to the stages of the cradle-to-gate, waste processing, disposal and recovery. Figure 1 shows the cut-off criteria and system boundaries considered in the Lunawood EPD. Construction-installation processes and use stage are excluded from this declaration (RTS_180_22).

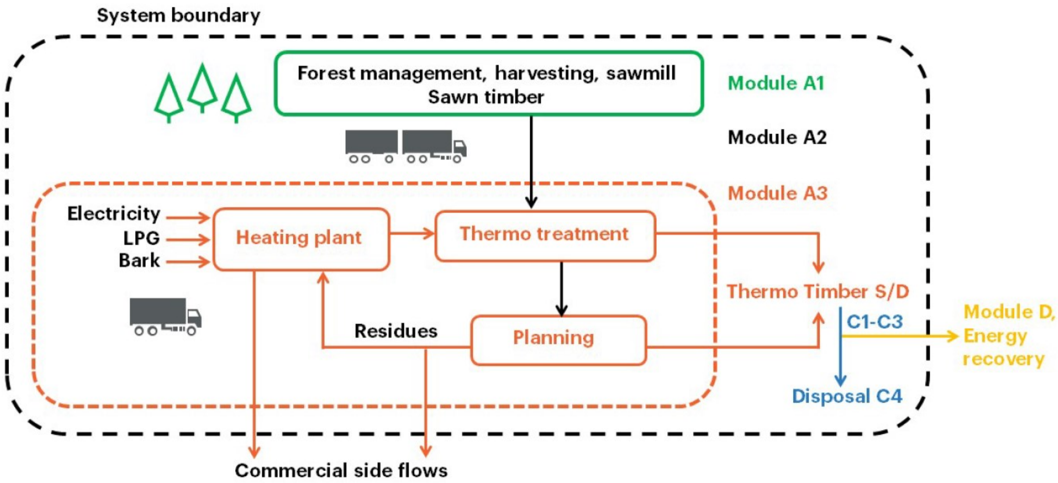


Figure 1. The cut-off criteria and system boundaries considered in the Lunawood EPD (RTS_180_22).

Lunawood's valid EPD covers raw material supply (A1), transport (A2), manufacture (A3), average transport distance to the customer (A4), end-of-life (C) and supplementary information beyond the life cycle such as energy recovery (D) (RTS_180_22). This eliminates the lifecycle effects during use phase. The purpose of this work is to perform a life cycle assessment of Lunawood ThermoWood® products using cradle-to-grave approach, which also takes into account the effects during use phase in selected countries. It is important for Lunawood to show their customers and end-users the carbon footprint of ThermoWood® products.

Globally, there are many challenges in the timber trade, like corruption. Also, following practices are not common at global level, like logging forest resource assessment methods, harvest planning, sequences of annual harvesting coupes and socio-environmental impacts assessments. Despite these challenges, it is believed that gradually sustainable forest management will support governance and global timber supplies. It is estimated that 204 million m^3 of tropical forest per year is harvested in member countries of the International

Tropical Timber Organization (ITTO), which represents 80% of the world's tropical forests. However, 87 % of tropical deforestation is illegal. The timber trade of illegal tropical timber is about $ 30-100 billion/year. (Sasaki et al., 2016).

Lunawood's timber suppliers have either PEFC or FSC certification, or both. Lunawood has a PEFC certificate that tells customers for example that the timber used by Lunawood has not been sourced illegally. Also, PEFC certification (PEFC 2014) guarantees that biodiversity is taken into account although research suggest more should be done (Kuuluvainen et al. 2019).

In 2021, there was a strong demand in the global level for Finnish sawn timber procured from legal sources. There have not been enough suppliers, so globally the export price level has also risen to a record high, up to 40 % higher than in 2020. The sharp rise in prices started in the United States. In 2021 the change in the production volume of planed sawn timber in Europe was + 63% and the change of price was + 14 % compared to the first quarter of 2020. Year 2022, global demand for sawn timber is expected to be good. Sawmills have responded to the growth in demand for sawn timber, e.g. by investing in new sawing lines (Viitanen et al., 2021).

The Finnish Forest Industry, the Finnish Sawmill Industries and The Confederation of Finnish Construction Industries RT must also play their part in meeting the sustainability challenges associated with the use of forests, such as nutrient recycling, climate change and adaptation, and biodiversity. Many large sawmills have their own sustainability and environmental programs, like MetsäGroup (Metsä Group, 2022), UPM (UPM, 2022) and StoraEnso (Stora Enso, 2022). The smallest sawmills follow sustainability program of the Finnish Sawmill Industries. What all of these have in common is that efforts are being made to influence the sustainable use of forests.

In this work, carbon footprint of Lunawood ThermoWood® cradle-to-grave is defined by evaluating global warming potential (GWP) accordingly to the Life Cycle Assessment (LCA) methodology as defined in the ISO 14040:2006 (2006) and ISO 14044:2006 (2006). The GWP of Lunawood ThermoWood® is compared with the GWP of tropical wood Light Red Meranti and Dark Red Meranti (Ratnasingam et al., 2015). Also, in this study it will be studied whether the environmental impacts of in-house production differ between mills, and how the global warming potential is affected by in-house planning compared to planning by the subcontractor.

The objectives of this study are to assess carbon footprint of Lunawood ThermoWood® products from cradle-to-grave approach when use phase is located in the United Kingdom (UK), Germany, the United States (USA) and South Africa by using life cycle assessment methodology and to provide information on global warming potential (GWP) to support marketing. The information found through this study will be used to improve the environmental sustainability of Lunawood's products. In this study, thermally modified wood and planed thermally modified wood are examined. The product called Luna Triple 32x140 is planed in-house and Luna Layer 19 x 142 is planed by a subcontractor. Thermo timber is thermally modified wood without planning. When calculating the carbon footprint, emissions caused by investments, equipment and machines, and emissions from buildings are not taken into account. Emissions from land use are also not taken into account.

2 Sustainability in thermally modified timber business

The sustainability of thermally modified products is influenced by the sustainability programs of the Finnish Forest Industry, Finnish Sawmill Industries and The Confederation of Finnish Construction Industries RT. These associations highlight the three main sustainability challenges to be addressed: nutrient recycling, climate change and adaptation, and biodiversity, which are key themes in UN Sustainable Development Goals 13 (Climate Action) and 15 (Life on Land).

2.1 UN Sustainable Development Goals (SDGs)

The 17 UN Sustainable Development Goals (Figure 2) form the core of the 2030 Agenda for Sustainable Development. Agenda 2030 aims to eradicate extreme poverty and develop sustainable development, taking into account people, the environment and the economy (United Nations).

Figure 2. UN Sustainable Development Goals (United Nations).

The drivers of sustainable development are social, technological, economic, ecological, political and also, many parties include legislation and culture as well. Each UN SDGs have detailed goals and sub-goals to meet global challenges. Various stakeholders have chosen from these 17 UN Sustainable Development Goals the most suitable ones. With these, companies are striving to set themselves even more ambitious goals in order to achieve the goals of Agenda 2030.

2.2 Sustainability challenge of Finnish Forest Industries

Finnish Forest Industries has drawn up its own climate roadmap, in which the goal is that by 2035 Finnish Forest Industries' member companies will no longer use fossil fuels. The forest industry makes products from wood in which the carbon is bound from the atmosphere. From a societal perspective, the forest industry employs and maintains a sustainable economy. Exports of forest industry products, such as paper, packaging hygiene products and chemicals, increase domestic wealth. The forest-based industries have a major impact on climate change and adaptation. It has been calculated that the climate benefit of wood-based products in Finland is more than 16 M CO_2 tonnes per year, as wood-based products replace more fossil-emitting products. (Metsäteollisuus ry (a), 2021). Numerous companies in the forest industry have made a lot of investment to make their operating environments almost carbon neutral. For example, companies in the forest industry have their own biopower plants to produce renewable energy for the plant's needs. Finnish Forest Industries does a lot of awareness work and advises forest owners to manage their forests. When the forest is managed better, the trees grow better and therefore bind more carbon. In Finland, trees grow more that it is harvested. In this way, the carbon sinks of the forests are not reduced. The forest industry invests heavily in circular economy solutions and wood processing, which brings more economic and climate benefits. By 2035, the value added of the forest industry is estimated to be about 300 billion euros, although the forest industry will slow down climate change through various actions. (Metsäteollisuus ry (a), 2021).

However, Finnish forest industry still accounts for about 5 % of total fossil CO_2 emissions in Finland although majority of fuels are bio-based in Finnish forest industry. From Finnish forest industry there are expected to produce more sustainable products and fuels to boost the transformation to biobased product producer. (Lipiäinen & Vakkilainen, 2021). Also, more investment from the forest industry to preserve biodiversity is expected (Seppälä et al., 1998).

New climate-friendly products are part of the long-term product development work that companies in the forest industry are constantly doing to increase their competitiveness. At the same time, the employment of Finns throughout Finland is secured, which means that the forest industry acquires diverse experts. Taxes and export earnings contribute to maintaining the Finnish welfare society (Metsäteollisuus ry (a), 2021).

Finnish Forest Industries actively participates in the implementation of Agenda 2030 in Finland together with various stakeholders. The forest industry's commitment to sustainability is part of the national commitment to sustainable development. The forest industry is a promoter of the sustainable use and diversity of forests by ensuring that the origin of wood is known and comes from legal sources. The leaching of nutrients from forests into water bodies is prevented and the voluntary protection of forests is promoted. On the other hand, the forest industry has a key role to play when it comes to mitigating climate change. The forest industry invests in energy-efficient solutions and does a lot of product development for climate-friendly products, as well as implementing a circular economy (Metsäteollisuus ry (b), 2020). However, Kuuluvainen et al. (2019) adds that Finnish forest management based on to a small extent of retention trees and final felling which means that biodiversity is declining. The change of the usual way of thinking is needed. Anyway, Finnish forests are PEFC and / or FSC certified, which is an important factor in tracing the origin of the wood. This makes it easier to do life cycle assessment.

2.3 Sustainability challenge of Finnish Sawmills Association

Finnish Sawmills Association was founded in 1945. Its goal is to control the interests of about 30 small and medium-sized member companies by promoting their business. The social and economic impact of Finnish Sawmills Association has been examined in a report involving 26 independent sawmill companies. The sawmill industry has a significant impact in various locations. Sawmills are important for local communities, as they bring in wage, tax and export revenues to their municipalities. On the other hand, the sawmill industry has been considered a reliable and long-term employer. The average length of employment is

14.5 years. Indirectly, sawmills employ 3 people per one direct job, for example in logistics and forestry. The sawmill industry regularly invests around 50 million euros a year so that investment debt does not become too high. The investments will be used to improve e.g. material and energy efficiency of sawmills as productivity increases (Sawmill Industry (a), 2022).

Finnish Sawmills Association is helping to meet the sustainability challenges of the sawmill industry. With the help of the investments, the companies in the sawmill industry will improve e.g. own material and energy efficiency (Sawmill Industry, 2022). The sawmill industry has also drawn up its own forest environment program, which complements the requirements of the Forest Act and forest certification. The Forest Environment Program pays attention to the conservation of biodiversity, which is one of the sustainability challenges for the sawmill industry. Leaving protective zones prevents nutrients from leaching into water bodies. This is also an important measure from the point of view of responsibility. The sawmill industry also organizes online courses for its members on the forest environment program (Sawmill Industry (b), 2021).

2.4 Sustainability challenge of The Confederation of Finnish Construction Industries RT

According to The Confederation of Finnish Construction Industries RT (RT), the most important thing is to look at the building as a whole and during its entire life cycle when assessing the environmental impact. RT also points out that in the European Union and national regulations, targets must be set for the energy consumption and CO_2 emissions of buildings and even for regions when doing land use planning. It is up to industry to develop the necessary technologies to meet the set targets (Rakennusteollisuus RT (a)). Table 1 shows the sustainability challenges in the construction industry according to The Constructor (2020) and how the construction industry itself responds to them with the help of RT's carbon roadmap (Construction Industry RT (b), cited March 18, 2022) and Lunawood's response to these sustainability challenges.

Table 1. Sustainability challenges in the Confederation of Finnish Construction Industries (Rakennusteollisuus RT a, b) and how the construction industry (The Constructor, 2020) itself responds to them, and Lunawood's response to these sustainability challenges (Thermowood Handbook, 2021; Sustainability report of Lunawood 2021, 2022; Environmental Product Declaration RTS_180_22).

Sustainability challenge for the construction industry (The Constructor, 2020)	**How does the Confederation of Finnish Construction Industries RT respond to them?** (Rakennusteollisuus RT a, b)	**How does Lunawood respond to them?**
Global warming due to construction	Wood construction materials: Strengthening the carbon stock of structures of buildings	Environmental Product Declaration RTS_180_22: cradle to gate approach shows that Lunawood's ThermoWood® GWP is 117 kg CO_2 eq/m^3
Loss of biodiversity and natural habitants	More efficient land use planning	Collaboration with main and long-life sawn timber suppliers (Sustainability report of Lunawood 2021)
Acidification due to construction	Monitoring the processes	
Air pollution due to construction	Monitoring the processes	Kiln exhaust gas from combustion is recycled (Sustainability report of Lunawood 2021)
Toxicity due to construction	Non-toxic materials	ThermoWood® process is chemical free (Thermowood Handbook, 2021)
Water resource pollution due to construction	Water efficiency	Monitoring the water usage in the ThermoWood® process (Sustainability report of Lunawood 2021)
Deforestration due to construction	Land use: Land use emissions are reduced through more efficient land use planning	Raw material from sustainable managed forests and from suppliers with PEFC certificate (PEFC certificate, PEFC-COC-FIN-1521)

The Confederation of Finnish Construction Industries RT has a lot of work to do to address the sustainability challenges in the construction industry. Carbon dioxide emissions, resource and energy efficiency and the importance of design throughout the life cycle of a building are key measures that contribute to meeting the environmental impact of construction.

3 a Finnish pioneer in the ThermoWood® production

The Finnish ThermoWood® manufacturer Lunawood is a 20-year-old company founded by brothers from Eastern Finland. Lunawood produces Finnish pine and spruce ThermoWood® at mills located in eastern and western Finland. More than 95% of ThermoWood® production are exported worldwide. Lunawood has reference sites in more than 60 countries. The annual growth rate based on turnover is about 10 - 12%. Lunawood's production capacity is 160 000 m^3 per year (Lunawood, 2023).

Lunawood's ecosystem covers entire supply chain from cradle-to-grave. Lunawood not only employs its own 140 employees, but socially affects many different players. The data produced by these selected actors will be used in this study to get the most comprehensive picture of the carbon footprint of Lunawood's products. In figure 3 the Lunawood's Ecosystem is presented.

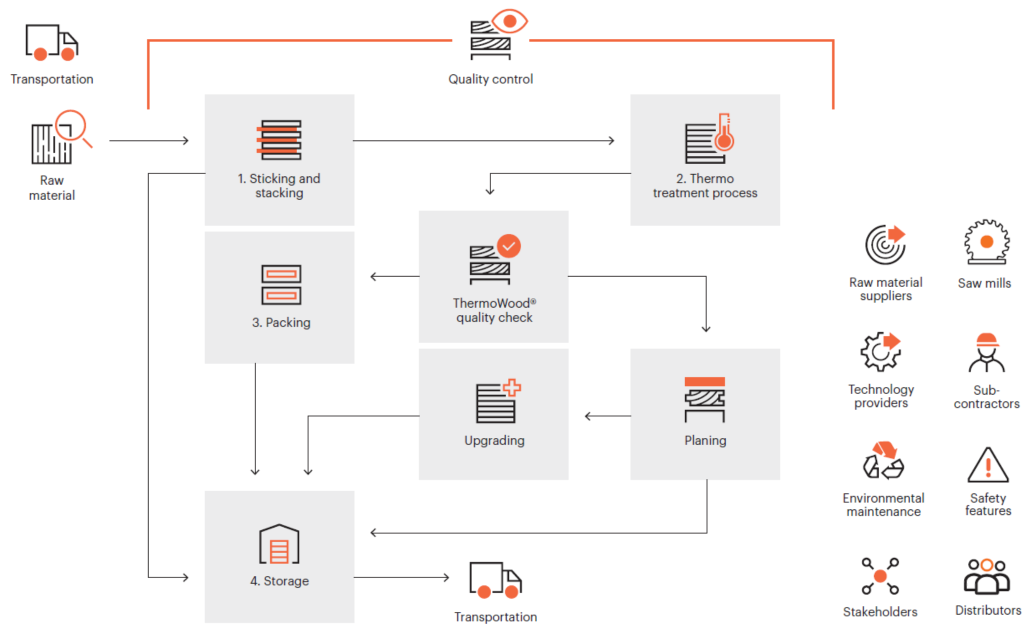


Figure 3. Ecosystem of Lunawood's illustrated by Jalo Toivio (2021).

This shows that the various stakeholders are needed to make world-class high-quality ThermoWood®. The aim of connections in the ecosystem is the profitability of the business. For some actions that are strongly related to corporate responsibility, it is sometimes difficult to determine the value in euros. The cost of implementing a sustainable action itself can be determined, but it is often challenging to determine the effect that actions, such as the marketing effect, will have. A sustainably operating company has to integrate social aspects into the decision-making process as much as environmental and financial sustainability. Social sustainability connects nature and its resources with human well-being (Husgafvel, 2021, Part 1). Figure 4 shows a four-field figure that brings together issues and actions from the perspective of sustainability that can be used to increase the value of a company.

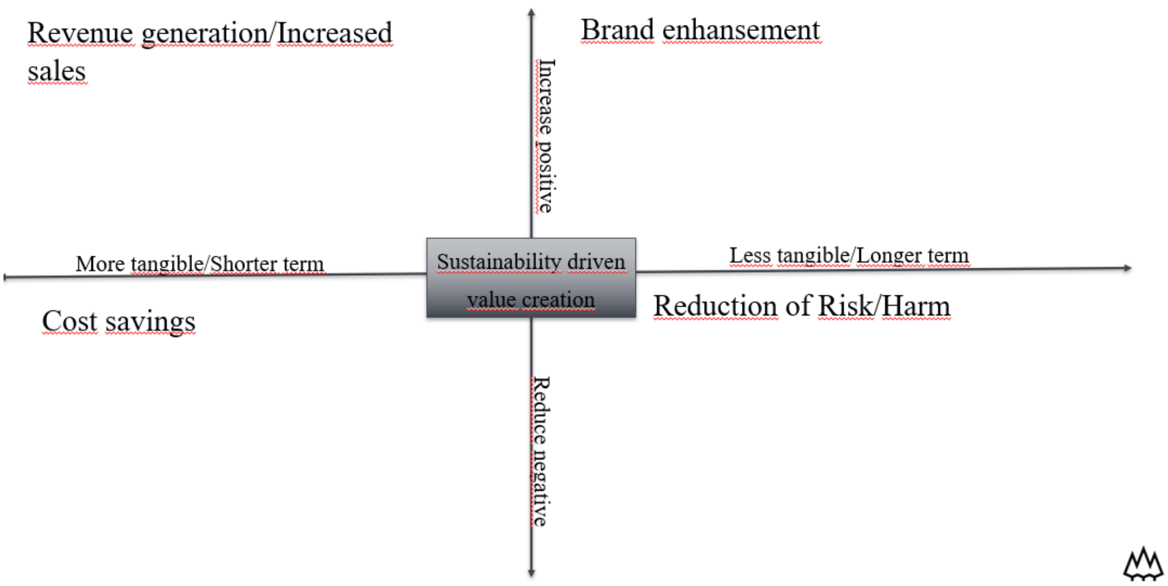


Figure 4. A sustainability-driven value creation framework (United Nations Global Compact, 2021).

Sustainability driven value creation takes into account not only economic sustainability but also environmental sustainability and social sustainability. A company must be able to generate value more efficiently than competitors in all areas of sustainability (Müller et al., 2012). The costs of the actions are easier to ascertain than the increase in value from sustainability communication or the measurable benefits of training the company's staff. Lunawood operates openly, fairly and sustainably throughout their value chain. Lunawood complies with laws and regulations, as is the case with most Finnish companies. Lunawood’s mission is to unite nature and people living in an urban environment, that is, to unite natural resources and human happiness and well-being. The most important resource for the Finnish ThermoWood® producer is its employees, whose well-being has been invested in many different ways, working conditions have been improved, ways have been sought to combine work and leisure, work safety is constantly being sought and wages can cope. These are the positive things that highlight the social and environmental sustainabilities that affect the conditions for life on the planet now and in the future (Husgafvel, 2021, Part 1). Lunawood want to do even more, such as integrating a corporate sustainability strategy into the company's overall strategy and communicating concrete corporate responsibility actions in all areas of corporate responsibility through a corporate sustainability communication plan. (Lunawood, 2022a).

3.1 Objective of UN Sustainable Development Goals at Lunawood

Lunawood has selected five UN Sustainable Development Goals (Table 2) that are consistent with Lunawood's daily business. Through these goals, Lunawood is committed to improving its own operations in a sustainable manner. The purpose of the sustainable development goals is to help improve Lunawood´s own operations, measure better them and achieve the set goals. As shown in Table 2, Lunawood has taken and is taking actions to help achieve selected UN Sustainable Development Goals in four operational areas: Certified Nordic raw material, Responsible production, World-class sustainable company and High-quality products with a long-life cycle.

Table 2. The United Nations Sustainable Development Goals to which Lunawood is committed (Sustainability Report 2021 of Lunawood, 2022).

	Decent work and economic growth	**Sustainable Cities and Communities**	**Responsible consumption and production**	**Climate action**	**Life on Land**
SDG	8	11	12	13	15
Goal of Lunawood	Upgrading woodproducts to higher economic value. Labour rights, safe and secure working environment. Equality in the workplace.	Wood as an outdoor and indoor construction material and future aspect of construction business.	Sustainable production including efficient energy and water use and waste management. Recycled Lunawood products can be used for energy production.	Improving renewable energy use. Carbon footprint of the products. Our products act as carbon sink.	Sustainable forest management. Responsible sourcing and replacing of tropical wood.
Actions to achieve the goal	Strong marketing actions to highlight Lunawood collection. To engage employees to develop Lunawood operations.	To follow actively the latest researches. Architect and designer support and promotion in the selected core markets. Lunawood Urban Challenge concept to create awareness of Lunawood among architect students.	Monitor environmental impacts. Emphasize Lunawood quality.	To work for low carbon map and LCA. Plan for energy transition to 100% renewable.	FSC certification, Save the Pollinator -campaign, Biodiversity programme with schools

The basic features of the business are the pursuit of operating profit. Lunawood wants to grow as it is planned with bringing a good working condition to its employees (SDG 8). It is important to monitor continuously how sustainable construction are reflected in cities and different communities. Lunawood is developing products for the sustainable cities of the future. That is one reason why Lunawood emphasize product's R&D actions and will not release semi-finished products into the market (SDG 11). The responsibility of production and the development of its energy efficiency are of paramount importance in energy-intensive sectors like at Lunawood (SDG12). All parties must be involved in mitigating and adapting to climate change. At Lunawood, investments and business decisions are strongly related to mitigating and adapting to climate change. The Environmental Product Declaration (EPD) for Lunawood ThermoWood® products is updated. To understand in comprehensive way the carbon footprint of thermally modified wood products this study is done which has been taken into account also CO_2 emissions during use, recycling and disposal phases (SDG 13). The goal is to maintain biodiversity as well. Lunawood works with raw material suppliers to tell customers around the world how in Finland attention has been paid to biodiversity. Lunawood is running a project with schools to inform schoolchildren about the importance of biodiversity and build insect hotels for pollinators with them. Lunawood provides its customers with insect hotels made from side stream of ThermoWood® production (SDG 15). These UN Sustainable Development Goals will help Lunawood meet the sustainability challenges associated with the forest industry. (Lunawood, 2003c).

On the other hand, in addition to sustainability challenges, there is a lot of unskilled labor in the construction industry that is also unfamiliar with materials. The properties of Lunawood ThermoWood® are divided into three different groups: technical, functional and sustainable properties. Figure 5 shows the properties of Lunawood ThermoWood® (Lunawood, ThermoWood® benefits, 2022).

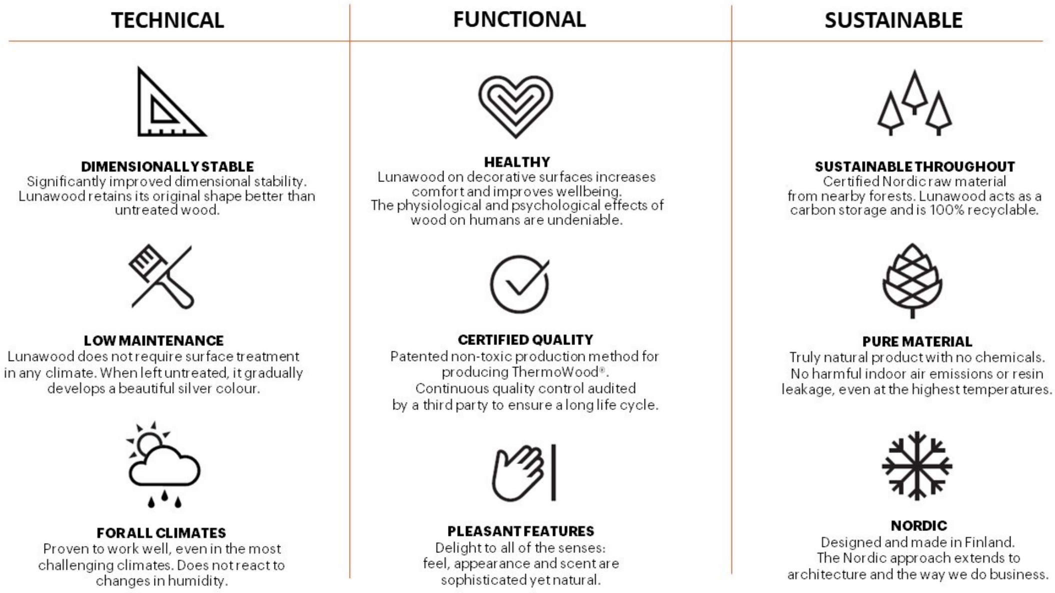


Figure 5. Characteristics of Lunawood ThermoWood® (Lunawood, ThermoWood® benefits, 2022).

It is important for the customer to know the properties of the product transparently. On the other hand, a thermowood installer needs to know what he is installing. Behind these features is a lot of product development and testing in the background in collaboration with several research organizations and institutions. Training related to ThermoWood® products is organized on behalf of the manufacturer.

From a sustainability perspective, ThermoWood® products are carbon storage that can meet the sustainability challenge of climate change and adaptation. More carbon is bound than produce CO_2 emissions per cubic meter (m^3) in Lunawood ThermoWood® production (Environmental Product Declaration RTS_180_22, 2022). No chemicals are used in the production of Lunawood ThermoWood® products, so there are no emissions to the environment. Environmental impacts and water consumption are monitored at all times. When installed well, ThermoWood® products last a long time and are timeless. The sawn timber used in the ThermoWood® production is inspected when it arrives at the factory, after the ThermoWood® process audited by a third party, the quality of the ThermoWood® is checked before it leaves the customer. The sawn timber that comes to Lunawood comes from certified sustainable managed forests.

3.2 Competitor analysis

Thermally modified wood is produced in several companies around the world. Thermory, Kebony and Accoya are not members of the International Thermo Wood Association, of which Lunawood is a founding member. The International Thermo Wood Association has published e.g. a guide that explains exactly how to produce ThermoWood® under the ThermoWood® brand. This process is audited by a third party, and it is developed in Finland, and members of International Thermowood Association are identified by the ThermoWood® trademark (Lämpöpuuyhdistys ry, 2017). The International Thermo Wood Association has 16 member companies from eight different countries. The task of the association is to promote the use of ThermoWood® products (Lämpöpuuyhdistys ry).

Thermory, Kebony and Accoya are the closest foreign competitors of Lunawood. These companies operate globally. Kebony and Accsys produce chemically treated wood. Thermory is using a different process than producers that are eligible to use ThermoWood® process to manufacture thermally modified timber. If we compare the products of Lunawood and Thermory, they are both thermally modified wood and have similar properties, although detailed information about the Thermory product is not available from their webpage (Thermory,2022).

Kebony has production facilities in Oslo, Norway and Antwerp, Belgium, where raw materials are transported from responsibly managed forests around the world. 63% of Kebony's carbon footprint comes from transporting raw materials. Kebony uses e.g. *Radiata pine*, alder, magnolia spruce and pine. The Kebony uses in its process furfuryl alcohol, which is obtained as a by-product of agricultural crop waste. In this process, locked-in furan polymers are formed in the cell wall of the wood. This year, Kebony released its first Sustainability Report, which clearly outlines their carbon footprint and emphasizes the UN Sustainable Development Goals they have chosen. Kebony has made it clear that the chemical used in the process is organic and made from agricultural by-products. In addition to these, the report highlights many important issues that are currently being addressed in the area of accountability, such as EU taxonomy. The report skillfully uses the GRI principles of reporting (Kebony, 2022).

Another major wood manufacturer, Accoya, comes from the United Kingdom. Accoya manufactures chemically modified wood using an acetylation process, which can accelerate the naturally occurring acetylation process in wood. This reduces the ability of the wood to absorb water. Accoya® is Accsys' brand for chemically modified wood. Accsys has an annual report and its own sustainability guide, which highlights the sustainability of Accoya's production process using a solution-focused presentation. The guide highlights how Accoya addresses the challenge of sustainability related to climate change (Accoya). From Accoya can be found in the carbon footprint of their various raw materials from cradle-to-gate. The carbon footprint of pine sourced from Scandinavia is 140 kg CO_2eq / m^3, while that of *Radiata Pine* sourced from New Zealand has a carbon footprint of 342 kg CO_2eq / m^3 (Accoya® wood, 2012).

Thermory produces thermally modified wood without chemicals using only steam and heat like Lunawood. Thermory does not say exactly what kind of production process they use. Thermory procures trees from responsibly managed forests around the world and transports them to Estonia or Finland, where their production facilities are located. Thermory does not publish a sustainability report. The website tells consumers how Thermory procures its raw materials, from logistics, manufacturing and product features, on a general level without numerical data (Thermory, 2022).

Table 3. Summary of Lunawood's competitor analysis.

	Lunawood **(non-chemical),** (Sustainability report 2021, 2022)	**Thermory (non-chemical), no Sustainability report**	**Kebony (chemical),** (Sustainability report 2022)	**Accsys - Accoya (chemical, but non-toxic),** (Sustainability report 2021, 2022)
Products	ThermoWood® & Composite TWPC	thermowood and timber	Impregnated wood. Pinus Sylvestris and Pinus Radiata	Acetylated wood products (Accoya) and panelproduct Tricoya
Carbon footprint [kgCO$_2$ eq/m^3]	117	N/A	353	140 – 342 depending on the raw material*
Technology & Production	using heat and steam, no chemicals	using heat and steam, no chemicals	Furfuryl alcohol Impregnated into the wood	Acetylated wood, Acetyl impregnated to wood
Virgin material	100 % Nordic forest	Wood is from Europe and North America. White ash tree is advertised but also thermo pine, radiata-pine, spurce, magnolia, aspen, alder	FSC wood from Sweden and New Zealand	100% of Accoya® and Tricoya® made from certified sustainable (FSC® or PEFC®) wood sources. Full compliance with EU Timber Regulation. from certified sustainable, fast-growing forests in low-risk regions
End of use/waste	Re-use: for ex. Wood chips Disposal: Energy production Secondary raw material utilization: thermowood fiber to TWPC composite	Disposal: energy production	N/A	Useful application through product and material re-use Disposal: energy production
Quality, Sertificates and ecolabels	PEFC EU Timber regulation UN Global Compact FIBS USGreen Building Council International KOMO certification Avainlippu CE Nordic swan ecolabel The international thermowood association BRE Ecocompass EPD: Cradle-to-gate	rot resistance up to 25 years or + Innovative joint solutions (JEM joint), ISO 9001, PEFC & FSC, CE - marking, Declaration of performance (DoP), Nordic swan ecolabel	FSC The United Nations Global Compact PEFC Nordic Swan Ecolabel Norwegian Green Building Council (NGBC) SundaHus ENvironmental Data	50 years warranty above ground and 25 years warranty in ground or fresh water potentiel service life of 70+ years FSC forest (100% certified) International KOMO certification Cradle to Cradle C2C Gold overall and C2C Platinum for Material Health Non-Toxic Statement Nordic swan ecolabel LEED, BREEAM, Green Star certification, Declare label Green Label of the Singapore Environment Council (SEC), Dubokeur certificate International Wood Products Association award (IWPA)

*(Accoya® wood, 2012)

Although the manufacturing process of Kebony and Accoya is chemical, while the manufacturing process of Lunawood and Thermory is based on heat and steam, they are competitors because they all operate globally and manufacture products for the same purpose. All of them have products that can be used for outdoor and indoor upholstery, on terraces and in saunas. Each operator presents its' sustainability and related measures in its' reports, except for Thermory, and on its websites.

The carbon footprint of Lunawood is compared in this work to Malaysian tropical hardwood Light Red Meranti and Dark Red Meranti (Ratnasingam et al., 2015). Tropical hardwood competes with thermally modified wood due to similar use. Logging of tropical hardwood is not always legal and there is a lot of corruption around it (Sasaki et al., 2016). Sustainability and sustainable operations act as a competitive factor in PEFC and FSC certified forests (PEFC; FSC).

4 ThermoWood® process and its characteristics

The ThermoWood® manufacturing process is suitable for hardwoods and softwoods, but it must always be optimized to suit each type of wood. The ThermoWood® process is a three-step process shown in Figure 6. In the first stage, the kiln temperature is rapidly raised to 100 ° C. The temperature is then raised to the desired temperature, for example 212 ° C. At this point, the wood dries out and the moisture content of the wood changes from about 20% near to zero. This step takes about 24 hours (Thermowood Handbook, 2021).

In the second step, the wood is thermally modified at the desired temperature. This step takes a few hours. In this stage, the moisture content is 0. At the same time, extractives, like resin, waxes, terpenes, phenols, are removed from the sawn timber. The ThermoWood® changes to a dark brown colour because the chemical properties of the wood change during heat treatment (Thermowood Handbook, 2021).

The third stage is called the cooling stage, in which the temperature is lowered step by step with a water-spray system. In this way, the moisture content of the ThermoWood® can be increased to 4 – 7 %. The total duration of the Thermoood® process varies depending on the type of thermal modified timber being made (Thermowood Handbook, 2021).

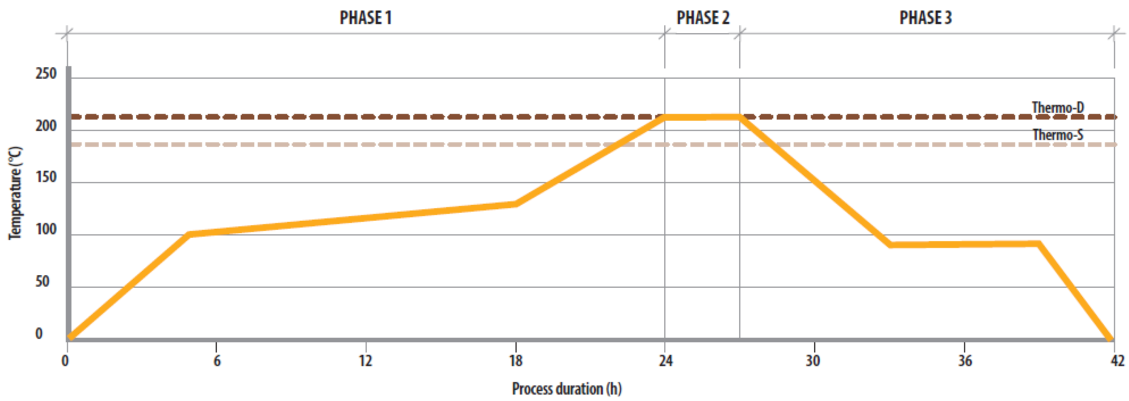


Figure 6. ThermoWood® process of Nordic softwood, class Thermo-D (Thermowood handbook, 202).

During the thermal modification of wood, the structure of wood cellulose and hemicellulose carbohydrates changes. Most of the changes occur in hemicellulose. At temperatures below 300 ° C, cellulose decomposes, which reduces polymerization. This removes water from the cellulose molecule and generates free radicals, carbonyl, carboxyl and hydroperoxide groups, carbon monoxide, carbon dioxide and reactive charcoal. The removal of water in the ThermoWood® process makes the ThermoWood® dimensional stability. Acetylated hemicellulose releases acetic acid, which acts as a catalyst, breaking down hemicellulose into smaller sugars and breaking down cellulose into shorter molecules. These chemical changes make thermo treated wood more resistant to fungal decomposition than ordinary sawn timber. Decomposition of hemicellulose has less of an effect on wood durability than decomposition of cellulose decomposing at 240-350 ° C. In the ThermoWood® process, the temperature is not raised to the decomposition temperature of the cellulose (Thermowood Handbook, 2021).

Lignin is found in the cells of a tree. During the ThermoWood® process, when the temperature is above 200 ° C, the lignin bonds begin to break down. In this case, the properties of the lignin change, such as color, reactivity and dissolution. There are also other compounds in the wood that evaporate during the heat process, such as terpenes, fats, waxes and phenols. ThermoWood® is not toxic. This has been demonstrated by the Daphnia magna and marine luminescent Bacteria test. During the ThermoWod® process, the pH of the ThermoWood® decreases, making it more acidic than ordinary sawn timber. Therefore, acidity may affect the non-attachment of organisms to the surface of the wood. When using ThermoWood®, it is important to remember to use acid-resistant or stainless steel (Thermowood Handbook, 2021) as fasteners.

4.1 Products chosen for carbon footprint assessment

The following Lunawood ThermoWood® products were selected for the life cycle assessment: Luna Triple 32x140, Luna Layer 19x142 brushed and Thermo Timber. These products are used in both indoor decorative surfaces and outdoor facades.

4.1.1 Luna Triple 32x140

Luna Triple 32x140 is manufactured at Lunawood 's mill in Eastern Finland. First, the sawn timber is processed in a ThermoWood® process, and then the ThermoWood® is planed in the mill in Eastern Finland Lunawood's own planing plant. This product can be used in interior and exterior. Luna Triple looks like a bar that emerges from two deep grooves planed on a board. This product was selected for the life cycle assessment so that Lunawood can evaluate the effects of their own planing on the life cycle assessment of the ThermoWood®. Figure 7 is Luna Triple 32x140.

Figure 7. Luna Triple 32x140 (photo: Lunawood).

The Luna Triple 32x140 is a best-selling profile developed in collaboration with the Belgian Stevens C ° (Stevens C °). This product meets the visual need of architects for a slatted wall, but also attracts installers with easy installation. This profile is not available in every competitor. The product is ingeniously executed. It launched Lunawood's 3D product family.

4.1.2 Luna Layer 19x142

Luna Layer 19x142 brushed is manufactured at the Lunawood's mill in Western Finland. After the ThermoWood® process, the product is transferred to the Aureskoski planing plant, where the thermo modified board is planed and brushed. Luna Layer is used as an indoor panel in various applications. This product was chosen for the life cycle assessment because it allows us to assess the impact of the planing of the subcontractor on the life cycle assessment of the finished product. Figure 8 shows Luna Layer 19x142 brushed.

Figure 8. Luna Layer 19x142 brushed (photo: Lunawood).

The idea for this product was to develop a broad product that increased the value creation of spruce raw material for its own Lunawood collection. Lunawood has not had a chip lap product in the collection before. The need for this came to the fore as Lunawood launched a project for the US market to expand their business operations. The profile is a very traditional “nickle gap”, meaning that the nickel coin fits in a tight groove, but the brushed surface creates interest and rusticity in the product. Lunawood does well as such a wide product because it doesn’t cup as untreated wood would certainly do in such a wide dimension.

4.1.3 Thermo Timber

For comparison, we also find out the life cycle assessment of the ThermWood® produced at the mills in Eastern and Western Finland. This information helps us evaluate the energy efficiency of the manufacturing process in different mills and the impact of the fuel used in the mills on the life cycle analysis of the ThermoWood®. Figure 9 shows Thermo Timber.

Figure 9. Thermo Timber (photo: Lunawood).

Thermotimber's customers are planer lines, but also other industrial end customers such as window manufacturers, outdoor furniture makers and spa makers. However, most of the

Thermo Timber goes into further planing and eventually ends up as exterior cladding or terrace products in the project business or in self-designed projects. This is potential to do-it-yourself projects.

5 Carbon footprint calculation methodology

Life cycle assessment (LCA) is one method used to measure the environmental impact of products. This tool is used to find out what inputs are needed to manufacture a product and what outputs are generated in the manufacture of a product. The aim is to identify those points in the process where the environmental impact could be reduced, for example by modifying the process or the inputs needed for the process. The results of LCA are used to communicate the environmental impact of a product to various stakeholders. LCA is commonly used e.g. environmental product declaration (EPD) in the preparation, marketing and various calculations describing the environmental performance of a product (ISO 14044).

LCA often involves assumptions and estimates because data may be collected from different countries and sources, units vary, and data is not only collected for LCA purpose. LCA data selection is often a subjective choice mainly because if there is not enough quality data available then it is needed to make the best possible estimate, which may overestimate the reliability. This may lead to incorrect estimates of the product's environmental impact. Programs designed for LCA calculation may contain incomplete information because data providers do not provide confidential information for fear of over-disclosure or misuse, but in many cases there are very useful tools. The data used in the LCA should be reliable and of high quality. To achieve this, attention must be paid to accurate and precise data collection and knowledge about a true value of quantity. (Björklund, 2002).

The ISO 14040 and 14044 standards describe the two key elements of an LCA: a) the assessment of the entire life cycle of the investigated system b) the assessment of the set of environmental impacts. According to ISO standards 14040 and 14044 (ISO 14040; ISO 14044), LCA consists of four main steps (Figure 10). An LCA begins with the Goal and Scope Definition. At first, it is necessary to point out why the research is being conducted. Then the product or process, the data sources, the functional unit, system boundaries, assumptions and limitations, data quality requirements, allocation procedures are taken into account. Also, if there are any doubts or critical reviews existing, they should be highlighted in the scope of the study. It is important also to describe the reference for all related inputs and outputs. In the scope of the study functional unit and system boundaries are described more thoroughly.

Functional unit is an important part of LCA. It should be chosen so that it best describes what is being researched. It serves as a reference to which input and output data are normalized which leads that the functional unit must be measurable and defined. The functional unit is used to compare the system under study with other similar systems. Also, all assumptions and limitations related to functional unit have to be explained and documented (ISO 14044:2006, 2006).

The processes that are considered in the LCA are highlighted in the system boundary's part. Processes must be relevant to achieve the set goal and they can be shown using a process flow diagram. Also, processes that are not considered in the assessment need to be identified at this stage. The collection of input and output data from published sources often required effort. At this stage, all the processes that cause significant environmental impacts in that assessment need to be identified, find data which full fill data requirements, and associated data with each of the unit processes. The data must be a comprehensive, precise and representative of the product system under investigation. If it is necessary of the assessment data must be collected over time, taking account geographical differences and how reliable the data is (ISO 14044:2006, 2006).

In the Inventory Analysis (LCI), the data collection and calculation procedures are described. The relevant input and output flows should consider the entire life cycle, usually consisting of a number of stages such as: materials extraction, processing and manufacturing, product use, and product disposal. The potential impacts of these inputs and outputs are then determined by the Impact Assessment (LCIA), which considers impact categories such as e.g. the global warming potential, acidification and eutrophication.

The final stage of the LCA is the interpretation phase, in which the results of the inventory analysis and impact assessment are interpreted, combined and processed to achieve the Goal and the Scope of the study. In the interpretation, attention must be paid to the uncertainties associated with the inputs and outputs data and the compounded effects of input uncertainties and data variability using value ranges or probability distributions. On this basis, conclusions and recommendations will be issued, as appropriate, to support the decision. The processed data can be presented in various forms, such as tables or matrices. (ISO14044).

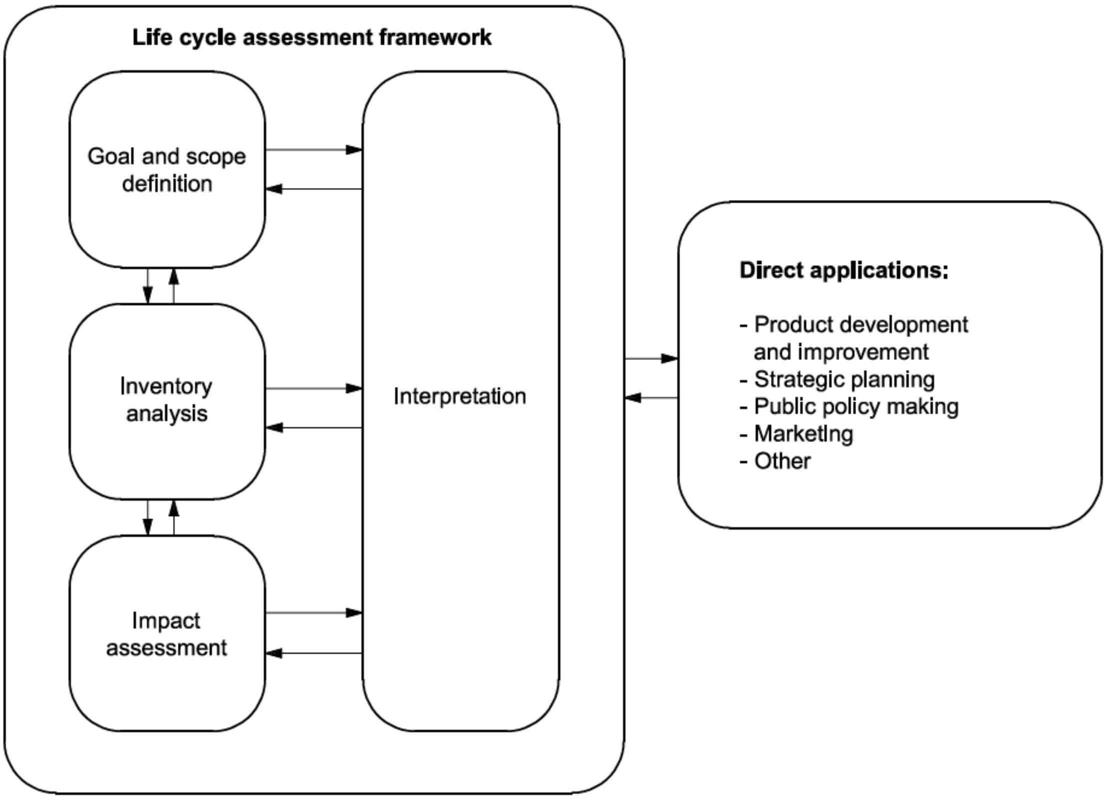


Figure 10. Main steps of LCA (ISO 14040).

Life cycle assessment has been an important tool in the construction sector since 1990. LCA has been used e.g. in the assessment of the environmental impact of building materials and their combinations and of the whole construction process. LCAs for building materials are not always comparable because the end products are different. Still, ways and methods are needed to determine the environmental impact of building materials and embodied carbon. This allows for the sustainable development and comparison of building materials. The life cycle assessments of construction projects are complex compared to the life cycle assessment of an individual product, e.g. because the age of buildings is often longer than that of an individual building material. States and different stakeholders have an important role to play in achieving different environmental policies to promote sustainable construction (Ortiz et al., 2009).

5.1 Allocation methods

The purpose of the allocation method is to clearly allocate the inputs and outputs of the system processes to the different products of the system under study. The allocation must be justified and documented. The inputs and outputs allocated to the products must be equal to the sum of the inputs and outputs of the entire unit process before allocation. The allocation must be implemented in such a way as to respect the physical relationships between the inputs and outputs of different products, which change in the same proportion if there are changes. If physical relationships cannot be used in the allocation, then the allocation can be made on the basis of, for example, the economic value of the products. Allocation can be made between co-product and waste. In that case ratio of co-product and waste need to be identified if inputs and outputs shall be allocated to the co-products part only. Sensitivity analysis is required if more than one suitable allocation method is available. (ISO 14044).

5.2 Carbon footprint

The carbon footprint study calculates the potential impact of the product on global warming over the entire life cycle, taking into account the limitations made in the selected processes. The unit used is carbon dioxide equivalent (CO_2e). The data collection must take into account the system under study and the functions connected to it, the requirements for data collection and quality, assumptions, the stage of use, the time and the functional unit. In the same way as LCA, e.g. allocation procedures, restrictions and reporting must be taken into account. The functional unit must be the same and consistent in order for the objectives to be achieved and the comparison to be successful and possible. The boundaries relate to processes that are irrelevant to the carbon footprint and must be clearly marked. Processes that make up at least 80% of the carbon footprint are classified as significant processes. Emissions related to waste streams are included in the carbon footprint study if they are related to the process under investigation (ISO14067, 2018).

Guidance on the calculation and reporting of the carbon footprint and partial carbon footprint is provided in ISO 14067: 2018 (ISO 14067, 2018), which is based on the principles, requirements and guidelines set out in ISO 14040 and ISO14044 for life cycle assessment.

In this work, the carbon footprint of the thermally modified wood is compared to tropical hardwood, where the global warming potential (GWP) of different sub-processes is calculated and related it to the reference unit m^3. GWP is an index that takes into account the radiative forcing caused by emissions of units of mass of greenhouse gases at a given time, which is proportional to the corresponding emissions of carbon dioxide at a given time. The carbon footprint study focuses on the natural sciences, such as physics, chemistry, and biology. If the data produced by these fields of science are not available, then the social sciences or economics can also be used, if qualitative data are available. The carbon footprint analysis has included the LCA four steps outlined earlier in this chapter (figure 10.). The collected data on greenhouse gas emissions and removals are linked to the stage of the life cycle to which they belong (ISO14067, 2018).

Different impact assessment methods are used in LCA. In Europe, the CML impact assessment method uses center-point modeling according to common mechanisms, such as climate change (Antikainen et al. 2010; Sphera - Gabi solutions). The CML impact assessment method was developed in 2001 in the Netherlands by the Institute of Environmental Sciences, University of Leiden. The university's website contains more than 1700 data related to different flows (Universiteit Leiden), which can be used in various software (Sphera - Gabi solutions) to calculate the life cycle assessment. The CML impact assessment method uses kg CO_2 eq. This is the global warming potential (GWP) calculation, which calculates the potential greenhouse gas emissions in kg of CO_2 eq in relation to the CO_2 that serves as the reference gas. In these calculations, the agreed period is 100 years. Greenhouse gases have different coefficients for climate change because they affect climate change at different intensities. For example, the contribution of methane to global warming is 27 to 30 times more when compared to carbon dioxide, so the CH_4: CO_2 ratio is 1: 27-30 (EPA, 2022).

6 CASE: Carbon footprint using cradle-to grave approach of Lunawood's ThermoWood® products

In the following paragraphs show the calculation of the carbon footprint following the steps presented in the standards. The collected data, carbon footprint is performed according to the ISO standards 14040 and 14044. The calculation of global warming potential (GWP) is done in order to find out the environmental impacts of the thermally modified wood (ISO 14067) using CML impact assessment method developed by Leiden Universiteit (Universiteit Leiden).

6.1 Goal and the scope of the study

The goal of this study is to evaluate the carbon footprint of thermally modified wood products made by Finnish ThermoWood® manufacturer called Lunawood. From customers' perspective carbon footprint provides clear added value to thermally modified wood products when they are exported and marketed around the world. Carbon footprint provides a thorough picture of the competitiveness of ThermoWood® products relative to other competing products. The results will be used in company's own communications, marketing and developing supply chain and production processes. Because the results will be available to the company, there was no possibility to use calculation programs used for educational purposes.

Lunawood's products' carbon footprint cradle-to-grave approach takes into account the sourcing of raw materials from Finnish forests to sawmills. From sawmills sawn timber is transported to Lunawood's mills where the process of ThermoWood® occurs. Thermotimber and planed goods are exported around the world to partners who sell products directly to end users. Greenhouse gas emissions during use phase are estimated in this work. Finally, an assessment is made of the end-of-life status of Lunawood products in selected countries and compared to Malaysian tropical hardwood Light Red Meranti and Dark Red Meranti (Ratnasingam et al., 2015).

The Lunawood's mills in Eastern and Western Finland provide information related to actions at the mills and the ThermoWood® process itself. In the mills in Eastern and Western Finland, the functions of the ThermoWood® process are slightly different.

6.1.1 System boundary

Carbon footprint assessment cowers the following modules from raw material supply, transport, manufacturing, use phase, waste processing and disposal. Figure 11 presents system boundary of this study.

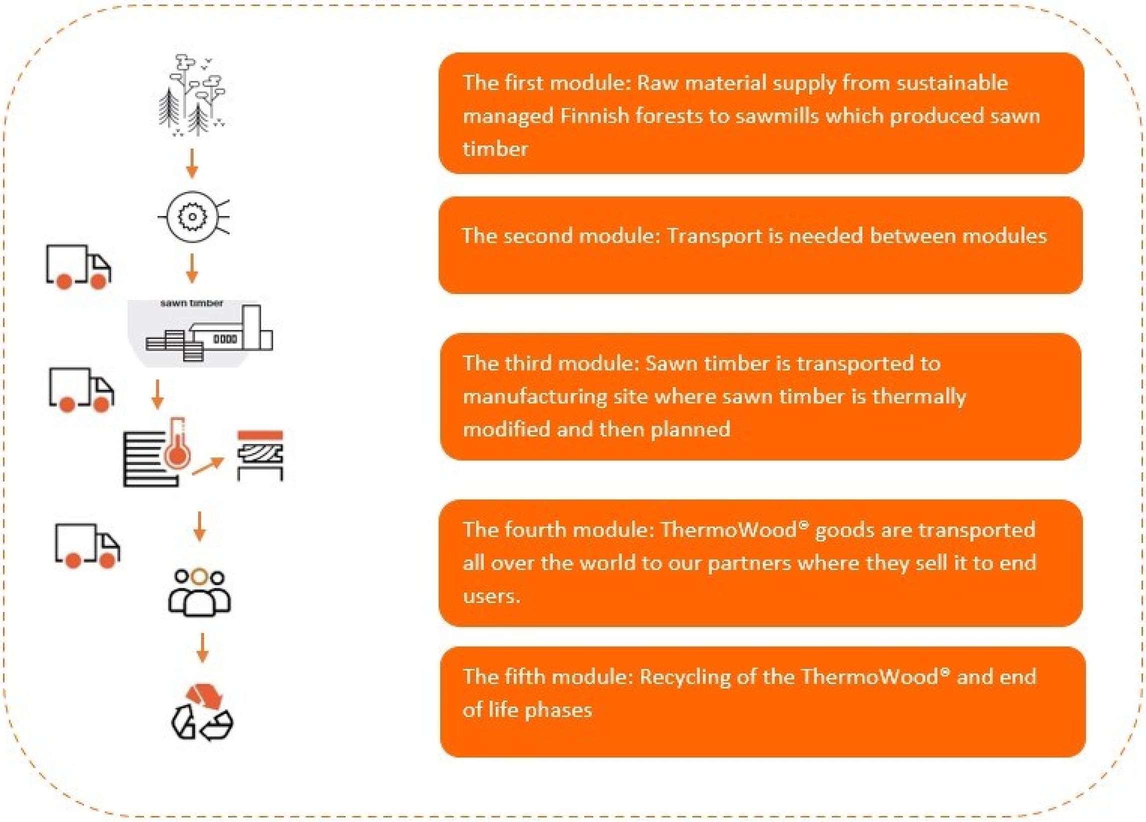


Figure 11. System boundaries of life cycle analysis of thermowood using cradle-to-grave approach.

The first module data includes raw material supply from the Finnish forests, transportation to sawmills and the production of sawn timber. The second module highlights transport with emission data from fuels as an energy. The third module consists of manufacturing phase of thermally modified timber and planed goods including used energy in mills in Eastern and Western Finland, packing materials, internal logistics and allocation process related to biocomposite terrace boards. The fourth module includes data from transportation (truck and sea freight) to Lunawood's partners which sell them to end-users including estimations of use time in selected countries USA, UK, Germany and South Africa. Data of the fifth module is related to end users and recycling and disposal of thermally modified wood in selected countries: USA, UK, Germany and South Africa. Inputs and outputs of the sub-processes are shown in following chapters. In this assessment factory buildings, process equipment and emissions from land use has not been taken into account.

6.1.2 Definition of Functional Unit

The cubic meter m^3 of thermally modified wood is used as the final unit of measurement, because e.g. raw materials are purchased in cubes, thermally modified wood production costs are calculated per cubic meter and transportation volumes are calculated in cubic meters. The outputs and inputs to be taken into account in the LCA are finally calculated to correspond one cubic meter. The choice of this functional unit increases the comparability of the results to research of Ratnasignam et al. (2015).

6.2 Life cycle inventory analysis (LCI)

The purpose of LCI is to collect data about the product system under study and find out if the scope of the study needs revision. During data collection, revisions of the goal or scope of the study may need to be done. Data is collected for smaller subprocesses within the system boundaries. The data must be validated, inputs and outputs for the unit process need to be calculated and relate the data per functional unit of the product system which is modelled (ISO 14040).

Data for this study are collected from Lunawood itself, Lunawood's partners, service providers, raw material suppliers, other material suppliers and logistics companies. Table 4 shows the steps involved in this carbon footprint assessment. Existing emission factors has been collected from various databases, companies and articles. The data consists of relevant outputs and inputs of a processes.

Table 4. All covered stages of this carbon footprint assessment from cradle to grave.

Raw material supply	**Manufacturing**	**Use stage**	**Recycling**	**End of life**
Forest machinery	Transport	Transport	Transport	Transport
Raw material production	Internal logistics	Service life	Reuse	Disposal
Transport	ThermoWood® process		Recycling	
Saw mill	Planning			
	Storage			
	Packing			
	Allocation: circular economy and selling the bioenergy			

The end-use service life has been estimated according to the trends of different countries. Recycling rate and energy consumption of thermally modified wood is estimated based on data from waste management and energy consumption in selected countries. The results have been calculated using values found in the literature.

No data was available for the carbon footprint calculation at the Aureskoski planning mill because they have not calculated their own carbon footprint. The Sawmill Industry EPD (RTS_124_21) was used to assess the effects of processing sawn products at mill in Western Finland. The product's service life was estimated with Lunawood's sales personnel and using the prevailing trends. Data of reuse, recycling and disposal of wood was sought from available waste management reports and energy production reports.

6.2.1 Allocation procedures

There are two allocation processes in this work that are taken into account: CO_2 emissions related to the generation of thermowood fiber from planed products at the mill in Eastern Finland and emissions from bioenergy generated at the mill in Western Finland and what is the share of CO_2 emissions related to sold bioenergy. Table 5 shows allocation procedures made in this master thesis work. The Lunawood's planning line in Eastern Finland produces thermowood fiber as a co-product, which is used to make terrace boards and thermowood pellets. The terrace boards are manufactured at Lunawood's mill in Eastern Finland. The raw material for the thermowood pellets is delivered from the mill in Eastern Finland to the manufacturer. This work evaluates how much of the production emissions are related to the thermowood fiber generated as a by-product of planing. The mill in Western Finland has its own biopower plant, where bioenergy is made for the mill's needs with bark chips which is a co-product of a saw milling process, and the extra energy is sold out.

Table 5 Allocation procedures made in this master thesis work are based on mass-allocation.

Allocation procedure	**Description of calculations**	**Allocation type**
Thermowood fiber generated by planing Thermowood® at mill in Eastern Finland mill	The share of Thermowood® fiber in the total Thermowood® production was calculated. Based on this, it has been calculated what proportion of Thermowood® fiber has been used for biocomposite and pellets. Based on these percentages the amount of CO2 emissions caused by the Thermowood ® fiber used for biocomposite production and pellet production in kg CO2 eq/m3, has been calculated from the total carbon footprint of the planed Thermowood® product. These CO2 emissions were reduced from the total carbon footprint of the planed Thermowood ®.	Mass-allocation is based on the allocation of amounts among different issues in a different case.
Sold surplus bioenergy	The share of energy sales in total energy was calculated. This proportion was used to calculate how much of the CO_2 emissions from the transportation of bark chips corresponds to the share of heat sales, and how much of the CO_2 emissions from the manufacture of wood chips corresponds to the share of heat sales. These calculated CO_2 emissions are reduced from the CO_2 emissions from the transportation of bark chips and the CO_2 emissions from the production of bark chips.	Mass-allocation is based on the allocation of wood chips used as energy.

6.2.2 Subprocesses related to the calculation of the life cycle life of ThermoWood®

The ThermoWood® production process begins with the sourcing of pre-dried sawn timber. Lunawood sources the Finnish spruce and pine from reliable sawmills all over Finland. The sawmills have at least a PEFC certificate. Lunawood has its own PEFC certification, so the chain of custody doesn't break. Therefore, the products leaving from the mills have a PEFC certificate (PEFC).

With sawmills, logs are sawn to the agreed dimensions. The sawmills have been given detailed instructions on what kind of timber is suitable for Lunawood accordingly to Lunawood's quality criteria. Lunawood uses central cuts of the logs (Figure 12). Bark chips which are a co-product of saw milling process at sawmills are used as fuel at the Lunawood's biopowerplant in mill in Western Finland as a fuel. Other users use other components of wood logs, like side boards. The whole wood log is utilized by different users in the forest industry.

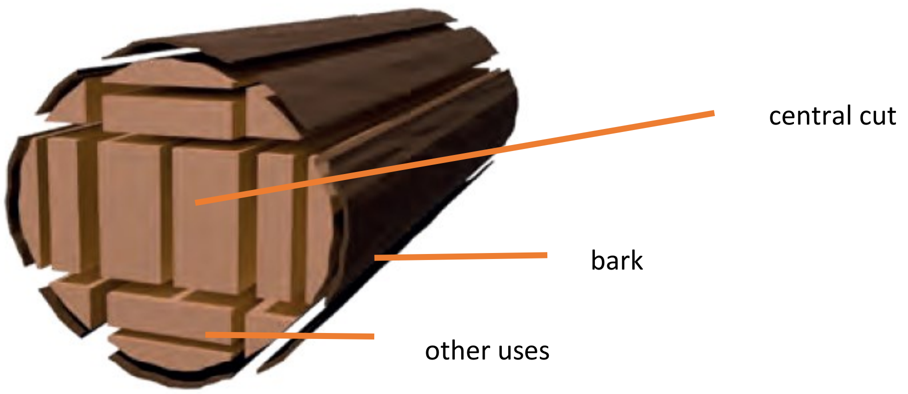


Figure 12. Parts of the wood log illustrated by Matias Laaksonen, Lunawood.

The sawn timber is transported to the mills in Eastern and Western Finland for ThermoWood® treatment process. For each incoming loads of sawn timber, a quality inspection will be performed. The wood load is then transported by forklift to a sticking and stacking plant, where the sticks and stacks are placed between the boards so that the thermo treatment takes place evenly on all sides of the wood. The timber with sticks and stacks is then transferred to the kiln by forklift. After the ThermoWood® process, an internal quality check is performed on the entire load. The thermally modified wood is determined for moisture, appearance, possible cracks and color. The kiln exhausted gases generated in the process are redirected for combustion. This prevents any emissions into the air from the process. After this step, the ThermoWood® is planed or sold as thermotimber. Luna Triple itself is planed in mill in Eastern Finland. Certain models are planed by a subcontractor as well. In mill in Western Finland, planing is done by a subcontractor. In mill in Western Finland, Lunawood is able to resell the extra energy to a subcontractor who planes the Lunawood's ThermoWood® patterns. After use, ThermoWood® can be recycled or used for energy production. In this work, it was also estimated CO_2 emissions of recycling and disposal of Thermowood® products. At the same time, it was calculated how much CO_2 emissions per square meter were from the manufacture of ThermoWood® products. This value [kg CO_2 eq/m^2] was used in the comparison, where ThermoWood® and planed ThermoWood® were used indoors for 10 and 20 years and outdoors for 30 and 50 years. Figure 13 shows the circular economy processes at Lunawood to highlight importance of circular economy and recycling processes. All part of the wood will be used by the different manufacturers whether as a wood products or as energy consumption.

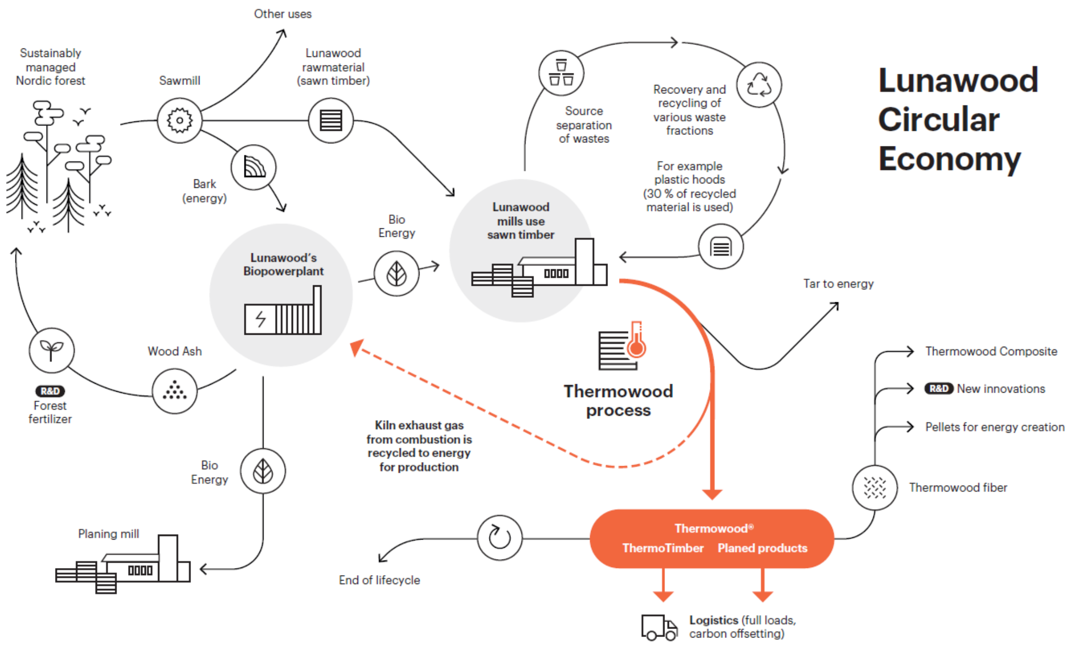


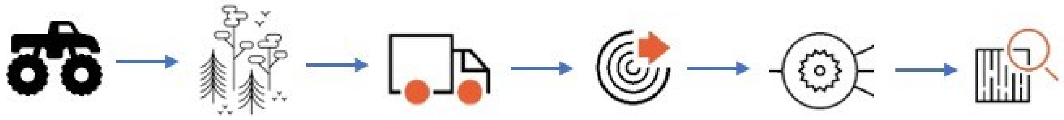
Figure 13. Circular economy at Lunawood, prepared by Kilpi-Koski and illustrated by Jalo Toivio (Sustainability report 2021 of Lunawood, 2022).

The circular economy is an important part of Lunawood's sustainability. It is not just the utilization of planed thermowood fiber in Lunawood's biocomposites or pellets. Kiln exhausted gases are reused as energy in the ThermoWood® manufacturing process, which improves the energy efficiency of the process. Because only steam and heat are used to make ThermoWood®, ThermoWood® can eventually be utilized for energy or recycled as any other wood products. The extra energy produced in the biopower plant will be sold on.

6.2.3 From forest to sawmills

Finnish spruce or pine is sourced from sustainably managed forests through reliable sawmill suppliers. From the forest, the logs are transported to the sawmill, where they are sawn into various sawn goods/dimensions. In Finland, every part of the wood is used, leaving nothing unused. Lunawood's thermally modified wood uses boards from the central cuts of the log. The branches and top are chipped, the top of the log is used to make pulp and the root system is either left in the forest to safeguard biodiversity or carbon storage or chipped. Table 6 shows the inputs and outputs of this step are shown.

Table 6. Inputs and outputs or raw material supply and sawn timber production at the sawmills.



Input	Process	Output	Data source
Wood from forest	Wood harvesting	CO_2 emission into air, wood logs, barks	
Fuel (energy) diesel	Forestry machine,	CO_2 emission into air	
Fuel (energy), diesel	Transportation to sawmill	CO_2 emission into air	Data provided by MetsäGroup
Fuel (energy), fossil fuel	Sawmilling	CO_2 emission, sawn timber	
Fuel,(energy), biomass	Electricity - Renewable		

This data is provided by MetsäGroup. Renewable energy from biomass is used in the sawmills. The electricity is produced with Metsägroup's own biomass, the emission of which is 0 kg CO2 eq/m^3.

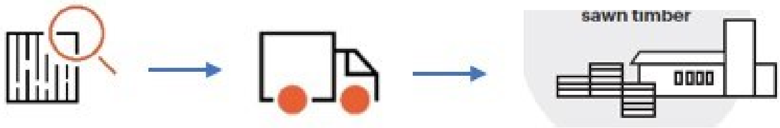
6.2.4 Transportation of sawn timber from sawmills to ThermoWood® production units

Lunawood's thermally modified wood is produced in mills in Eastern and Western Finland. Lunawood's ThermoWood® production began in mill in Eastern Finland 21 years ago. The mill in Western Finland has been acquired in 2016 from Metsägroup.

Mill in Eastern Finland

At the sawmills, the sawn timber is loaded to trucks that transport the sawn timber to the Lunawood's mills in either in Eastern Finland (table 7) or Western Finland (table 8). The aim is to load the trucks at full load. The average distance from sawmills to Lunawood's mills is 235 km but calculation mill specific distances have been used. In Tables 7 and 8 the inputs and outputs of this step are shown to.

Table 7. Inputs and outputs of transportation of sawn timber to mill in Eastern Finland.



Input	Process	Output	Data source
Fuel, diesel (energy)*	Transport of sawn timber to mill in Eastern Finland, used mill specific distance	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel, diesel (energy)	Forklifts (mill site)	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel, diesel (energy)	Transport of diesel for forklift **	CO_2 emission into air	Lipasto database by VTT, Lunawood
PP/PE raw material and its transportation and production	Plastic hoods covering sawn timber	CO_2 emission into air Plastic hoods as a side stream	Manufacturer Art-pak Oy, Lunawood
PET raw material	PET, plastic rib	CO_2 emission into air	Dormer et al. (2013), Lunawood

* This does not take into account the emissions caused by producing diesel from oil nor transport of diesel to Finland

**This does not take into account the emissions caused by producing diesel from oil

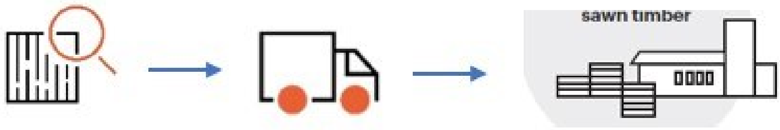
Annual CO_2 emissions of forklifts and transportation of fuel for forklifts at mill in Eastern Finland have been reported in the sub-process named Sawn timber from sawmills to Thermowood® production units. These CO_2 emissions is not divided by operations.

The data is collected from material suppliers, service providers, Lunawood and existing databases Lipasto provided by VTT.

Mill in Western Finland

In the mill in Western Finland coming sawn timber will be dried in the mill by bioenergy. This stage does not exist at the mill in Eastern Finland, because the raw material comes there dried. At the mill in Western Finland, surplus bioenergy is used to dry the raw material with zero emissions. Table 8 shows the inputs and outputs for this step.

Table 8. Inputs and outputs of transportation to mill in Western Finland.



Input	Process flow	Output	Data source
Fuel, diesel (energy)*	Transport of sawn timber to mill in Western Finland, used mill specific distance	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy)	Forklifts	CO_2 emission into air	from service provider monthly base CO_2 emissions, Lunawood
PP/PE raw material and its transportation production	Plastic hoods covering sawn timber	CO_2 emission into air Plastic hoods as a side stream	Manufacturer Art-pak Oy, Lunawood
PET raw material	PET, plastic rib	CO_2 emission into air	Dormer et al. (2013); Lunawood

* This does not take into account the emissions caused by producing diesel from oil nor transport of diesel to Finland

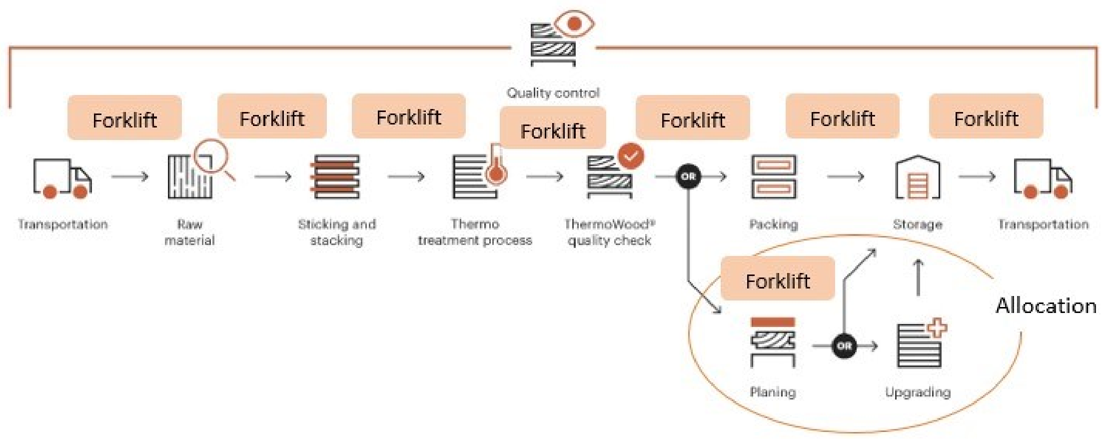
The data is collected from material suppliers, service providers, Lunawood and existing databases Lipasto provided by VTT.

6.2.5 ThermoWood® production process

Mill in Eastern Finland

In the Thermowood® production process in the mill in Eastern Finland there are many process steps need to be considered. The data is collected from Lunawood, energy company and service and material suppliers. Table 9 shows the inputs and outputs for this step.

Table 9. Inputs and outputs of ThermoWood® production in mill in Eastern Finland. The transportation on the left in the picture is already described above in tables 7 and 8.



Input	Process flow	Output	Data source
Energy used in Thermowood® manufacturing process	Liquefid Petroleum Gas (LPG)	CO_2 emission into air	Tilastokeskus, Sähkön ja lämmöntuotannon CO_2-päästöt, Lunawood
Fuel used in train and truck (energy), diesel	Transportation of LPG	CO_2 emission into air	Lipasto database by VTT
Electricity (energy)	Annual Electricity consumption at mill in Eastern Finland used in machines, in buildings, lights etc.	CO_2 emission into air	Provided by Väre, Energy company, Lunawood
Raw material, wood	Wood sticks	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association, Lunawood
Fuel (energy), diesel	Transportation of wood sticks	CO_2 emission into air	Lipasto database by VTT, Lunawood
Thermotimber, wood	Planing	Thermowood fibre	Lunawood
PP/PE raw material and its transportation and production	Plastic hoods covering out going thermowood package	CO_2 emission into air	Manufacturer Art-pak Oy, Lunawood
Fuel (energy), diesel	Transportation of plastic hoods from producer	CO_2 emission into air	Lipasto database by VTT, Lunawood
PET raw material	PET, plastic rib	CO_2 emission into air	Dormer et al. (2013), Lunawood
Fuel (energy), diesel	Transportation of PET, plastic ribs	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, wood	Bottom sticks	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association, Lunawood

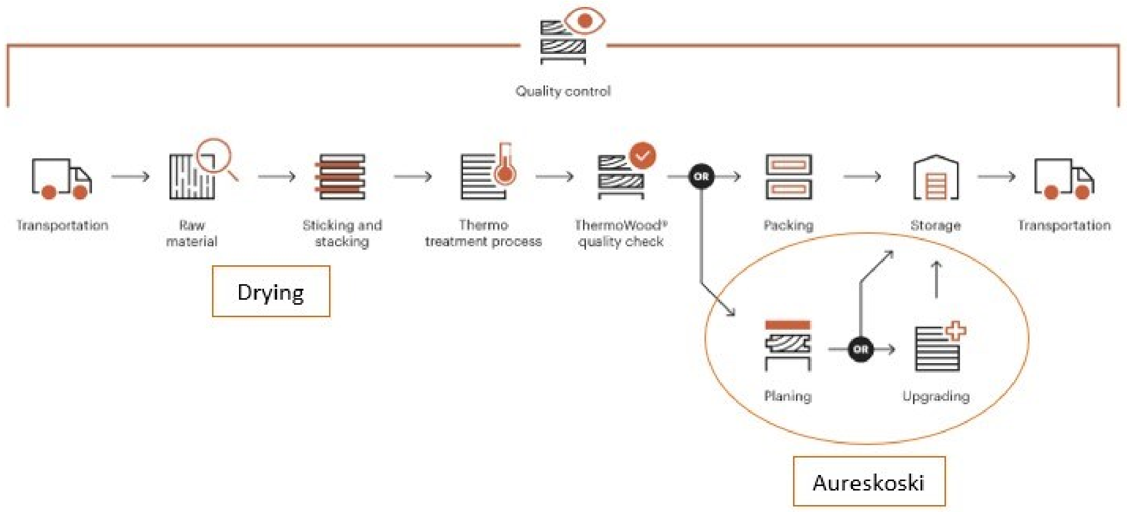
Fuel (energy), diesel	Transportation of Bottom sticks	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, wood	Sticks for between boards	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association, Lunawood
Fuel (energy), diesel	Transportation of sticks to use between boards	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, cartoon	Corner protection of the thermotimber package	CO_2 emission into air	WWF ilmastolaskuri, Lunawood
Fuel (energy), diesel	Transportation of corner protection of the thermotimber package	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, cartoon	Corner protection (small) of the thermotimber package	CO_2 emission into air	WWF ilmastolaskuri, Lunawood
Fuel (energy), diesel	Transportation of corner protection (small) of the thermotimber package	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, paper and glue	Tags for thermotimber packages	CO_2 emission into air	Aurapint Oy, Lunawood
Fuel (energy), diesel	Transportation of tags for thermotimber packages	CO_2 emission into air	Lipasto database by VTT, Lunawood
Energy	Hot oil as a waste	CO_2 emission into air	L&T, Lunawood
Fuel (energy), diesel	Transportation of hot oil as a waste	CO_2 emission into air	Lipasto database by VTT, Lunawood
Water	Steam	CO_2 emission into air	data from City of Turku
Wastewater	Wastewater treatment	CO_2 emission into air	data from City of Riihimäki

Allocation has been taking account in this stage of carbon footprint calculation. From the planing of the thermally modified wood at mill in Eastern Finland, also thermwood fiber is produced. Thermowood fiber is used in Lunawood's terrace boards. The rest of the thermowood fiber goes to the production of thermowood pellets. The share of thermowood fiber from total production of ThermoWood® is calculated. This will be divided between composite and pellets accordingly to their annual production. The mass-allocation process is explained in table 5.

Mill in Western Finland

In mill in Western Finland, the increase in production capacity was made possible by the mill's own biopower plant, which produces energy to heat the mill's buildings, the energy needed to dry the sawn timber and the hot oil needed to heat the kiln to the desired temperature. Some share of bioenergy is sold to Aureskoski planning plant. In table 10 inputs and outputs of ThermoWood® production at mill in Western Finland have been presented.

Table 10. Inputs and outputs of ThermoWood® production in mill in Western Finland. The transportation on the left in the picture is already described above in tables 7 and 8.



Input	Process flow	Output	Data source
PP/PE raw material and its transportation and production	Plastic hoods covering out going ThermoWood® package	CO_2 emission into air	Manufacturer Art-pak Oy, Lunawood
Fuel (energy), diesel	Transportation of plastic hoods from producer	CO_2 emission into air	Lipasto database by VTT, Lunawood
PET raw material	PET, plastic rib	CO_2 emission into air	Dormer et al. (2013), Lunawood
Fuel (energy), diesel	Transportation of PET, plastic ribs	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy), biomass	Bark production	CO_2 emission into air	Ghazanfari (2008), MetsäGroup, Lunawood
Fuel (energy), diesel	Transportation of bark	CO_2 emission into air	Lipasto database by VTT, Lunawood
Electricity (energy)	Annual Electricity consumption at mill in Western Finland used in machines, in buildings, lights etc.	CO_2 emission into air	Provided by Väre, Energy company

Raw material, wood	Wood sticks	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association, RTS_124_21
Fuel (energy), diesel	Transportation of wood sticks	CO_2 emission into air	Lipasto database by VTT
Raw material, wood	Sticks to use between boards	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association RTS_124_21, Lunawood
Fuel (energy), diesel	Transportation of sticks for between boards	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, wood	Bottom sticks	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association, Lunawood
Fuel (energy), diesel	Transportation of Bottom sticks	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, cartoon	Corner protection of the thermotimber package	CO_2 emission into air	WWF ilmastolaskuri, Lunawood
Fuel (energy), diesel	Transportation of corner protection of the thermotimber package	CO_2 emission into air	Lipasto database by VTT, Lunawood
Raw material, paper and glue	Tags for thermotimber packages	CO_2 emission into air	Aurapint Oy, Lunawood
Fuel (energy), diesel	Transportation of tags for thermotimber packages	CO_2 emission into air	Lipasto database by VTT, Lunawood
Energy	Hot oil as a waste	CO_2 emission into air	L&T, Lunawood
Fuel (energy), diesel	Transportation of hot oil as a waste	CO_2 emission into air	Lipasto database by VTT, Lunawood
Water	Steam	CO_2 emission into air	Data from City of Turku
Wastewater	Wastewater treatment	CO_2 emission into air	Data from City of Riihimäki

The mass-allocation process is used in relation to energy production, because excess energy is sold on. CO_2 emissions from the production and transport of the fuel used in energy production were allocated according to the ratio of sales and own use.

6.2.6 Aureskoski planning plant (Aureskoski)

ThermoWood® manufactured at mill in Western Finland is transported by forklifts to Aureskoski planing plant. Aureskoski is a subcontractor to Lunawood. ThermoWood® is processed by brushing at Aureskoski planning mill. This procedure gives the ThermoWood® a beautiful surface. The finalized products will be packed. In Table 11 shows only one process flow consisting raw material harvesting, transportation to sawmill and planning process.

Table 11. Inputs and outputs of planing mill.

Input	Process flow	Output	Data source
Raw material (ThermoWood®), transportation to planning, production	Planed thermotimber	CO_2 emission into air	EPD of Finnish sawn and planed timber by Finnish Sawmills Association (RTS_124_21)

This data of Finnish sawn and planed timber is taken from the EPD of Finnish Sawmills Association (RTS_124_21) because the Aureskoski planing mill has not calculated the CO_2 emissions caused by its own planing.

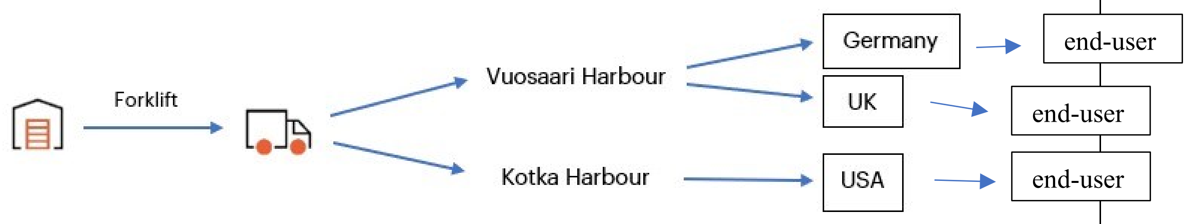
6.2.7 From mill to customer

ThermoWood® and planed Lunawood Collection products are shipped from to more than 60 countries. More than 95% of products are exported, of which more than 90% goes to the European market. Europe is a clear key market area. The market is currently in a pending state. The war between Ukraine and Russia has accelerated inflation in European countries, the price of fuel has risen tremendously and transportation for customers has become more challenging as Ukrainian drivers have gone to defend their own country. There are similar challenges in maritime transport. Sea containers have been packed around the world as return shipments have been delayed due to the lock downs caused by the pandemic. Transportation pricing are asked almost daily (Eila Härkin, 2022). All of these changes will affect the pricing and speed of transportation.

Mill in Eastern Finland

All products are transported from the mill to the harbor with full trailer trucks. The ThermoWood® products to the UK and Germany are transported from mill in Eastern Finland to Vuosaari harbor where the trailers are loaded to ship. This routing has been used when the situation in the world has been normal. Year 2021 Lunawood had had to look for alternative routes. The products from mill in Eastern Finland to USA are transported via Kotka harbor. In this work the so-called normal routing has been used. Table 12 CO_2 emissions from transportation from the mill to the customer are presented.

Table 12. CO_2 emissions from transportation from the mill to the customer for selected countries from mill in Eastern Finland.



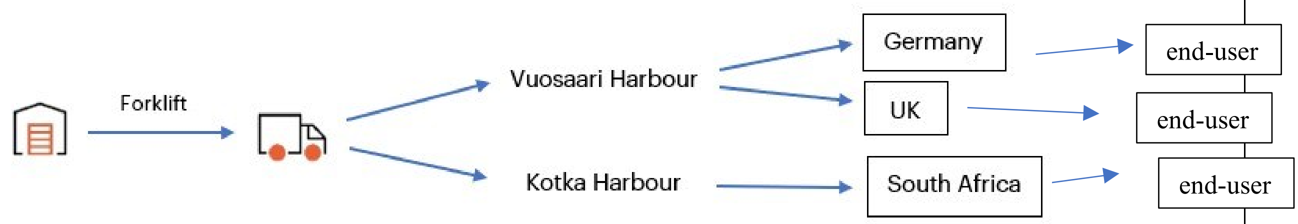
Input	Process flow	Output	Data source
Fuel (energy), diesel	Transportation from sawmill to customer Road transport and sea freight	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy), diesel	Transport from customer to end-user in Germany	CO_2 emission into air	Lipasto database by VTT, Lunawood, Lunawood's customer
Fuel (energy), diesel	Transport from customer to end-user in UK	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy), diesel	Transport from customer to end-user in USA	CO_2 emission into air	Lipasto database by VTT, Lunawood

CO_2 emissions caused by forklifts are taken into account already earlier sub-process of the mill. The distances from mill in Eastern Finland to Vuosaari and Kotka harbours are 470 km and 408 km, respectively.

Mill in Western Finland

The products to UK and Germany are transported to Vuosaari harbour where the trailers are loaded to ship. The products to South-Africa are transported via Kotka harbour where trailers are loaded to ship. Table 13 CO_2 emissions from transportation from the mill to the customer are presented.

Table 13. CO_2 emissions from transportation from the mill to the customer for selected countries from mill in Western Finland.



Input	**Process flow**	**Output**	**Data source**
Fuel (energy), diesel	Transport from sawmill to customer Road transport and sea freight	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy), diesel	Transport from customer to end-user in Germany	CO_2 emission into air	Lipasto database by VTT, Lunawood, Lunawood's customer
Fuel (energy), diesel	Transport from customer to end-user in UK	CO_2 emission into air	Lipasto database by VTT, Lunawood
Fuel (energy), diesel	Transport from customer to end-user in South Africa	CO_2 emission into air	Lipasto database by VTT, Lunawood

The distances from mill in Western Finland to Vuosaari and Kotka harbours 366 km and 453 km, respectively.

6.2.8 From Customer to end-users

In this study greenhouse gases during life cycle of wood products divided for service life (life time) [kg CO_2 eq/m^2/selected service lives in years] are compared by comparing different service lives and the square meters of thermotimber and planed thermally modified wood in outdoor and indoor spaces in selected countries Germany, UK, USA and South Africa (table 14). The carbon footprint of the ThermoWood® products per cubic meter [m^3] was converted per square meter [m^2] of thermally modified wood using the coefficient calculated by the Lunawood. The assessment of service life of ThermoWood® products is based on discussions with customers, salespeople's experiences of different markets and current trends in wood use. The service lives of ThermoWood® indoors could be even longer than 10 or 20 years.

In 2003, the Building Research Establishment (BRE) analyzed the technical data on Finnish ThermoWood® produced by VTT. In 2008, BRE published its own publication presenting the properties and performance of ThermoWood®. Based on these, BRE concludes that the expected service life of Lunawood Thermo-D used in UK exterior cladding is 30 years (BRE, 2008). No service life was found for wood products used as interior decorative surfaces. In this work, it was compared the service lives of Lunawood's ThermoWood® used in exterior cladding are 30 and 50 years and interior decorative surface are 10 and 20 years in each target country. In the study, the carbon footprint kg CO_2 eq/m^3 was changed kg CO_2 eq/m^2 and it was calculated how much greenhouse gases were generated in the production of different square meters.

Table 14. Estimated service lifes of thermally modified wood on interior and exterior surfaces, square meters used in the study to compare carbon footprint of thermally modified wood per m^2 and per service lives in years and estimated distances to the end-user.

	Service life of interior, decorative surface [year]		**Service life of outside, facades [year]**		**Surfaces of ThermoWood® [m^2]**	**Distance to customer [km]**
Germany	10	30	30	50	50, 100, 150	250*
UK	10	30	30	50	50, 100, 150	150**
USA	10	30	30	50	50, 100, 150	500***
South Africa	10	30	30	50	50, 100, 150	600****

*Klöpferholz (2021), Holzkurier 23, personal communication

**Estimation based on discussion with sales of Lunawood

***Estimation compared to size of Washington state

**** Estimate is based on the size of the distribution network

Table 14 also shows the average Lunawood's ThermoWood® distance to the end user. USA distance to customer is asset by size of Washington state. In South Africa, the distance from the port of Durban to the warehouse and from there to the end user has been estimated. In Germany, the distance is based on a figure given by Klöpferholz. Distance to enduser in UK is based on estimation of sales of ThermoWood® producer.

6.2.9 Recycling and re-use

Waste prevention and management

In all the selected countries, waste prevention and management are emphasized in the development of waste management hierarchy. This means increasing the circular economy, but also preventing the generation of waste. The products should remain in use as long as possible. Circular economy related actions can create more jobs, reduce the use of virgin materials and reduce greenhouse gas emissions. The EU Waste Framework Directive has two main goals: to prevent and reduce the negative impacts and to improve resource management (EU, Waste prevention and management). The waste Hierarchy in the EU (EU, Waste prevention and management), USA (EPA, Waste Management Hierarchy) and South Africa (Department of Environmental Affairs, 2011) is similar. All of them start from preventing the amount of waste, refurbishing products and extending their usefulness and lifetime, reuse, increasing recycling, energy recovery and disposal.

This work also aims to assess the effects of reuse and disposal on the environmental impact of Lunawood ThermoWood ® during its life cycle. Germany, UK, USA and South Africa have been selected as target markets. Every country is working to increase the re-use and recycling of waste and thus take actions for the benefit of the circular economy. Germany and the UK are monitoring and enforcing EU measures to improve the circular economy, waste re-use and energy efficiency. In the various German states, laws and regulations relating to waste management may differ. In the UK, since brexit, own legislation has been prepared, often based on the same principles as in the European Union. In the US, each state also has its own laws and regulations. The U.S. Environmental Protection Agency (US EPA) is a government agency responsible for environmental and health matters. The US EPA's programs are implemented in the states or based on its own programs, e.g. sustainable development. South Africa also has its own national waste legislation. Waste management improvements in South Africa have been made with the support of other countries and various international organizations.

Germany

In 2015, 401 million tonnes of waste were generated in Germany, of which 11.9 million tonnes were wood waste. Wood waste accounts for about 3% of the total amount of waste generated. The amount of wood waste consisted of wood packaging 21%, demolition and construction 26.7%, wood processing industry 14%, municipal wastes 20.7%, imported wood 9.7% and others from households and railway construction 8%. Previously, 20 years ago, wood waste was used for energy. Between 2013 and 2014, 34% of waste wood was utilized in the particleboards industry. In Germany, the aim is also to reduce the amount of wood waste going to landfill by increasing the efficiency of re-use, on which the new Renewable Energy Act is based. It is desired to use waste wood primarily for re-use and recycling. In the future, 40% of recycled wood waste can be recovered as a raw material in the production of particleboards or fiberboard and 25% could be other reused activities. Germany has also considered an approach to how wood waste can be collected, treated and distributed. Wood waste will be collected at recycling centers, after which it will be treated and delivered to customers through distribution centers (Garcia and Hora, 2017). Table 15 shows Lunawood's own estimate of how much of the ThermoWood® products used in interior and exterior cladding can be utilized. The second column highlights, based on citations, how waste wood is recovered and utilized in Germany (Garcia and Hora, 2017).

Table 15. Estimates of the utilization of ThermoWood® in Germany.

	Germany	
Reuse	evaluation by Lunawood	evaluation based on Garcia & Hora (2017)
• **Interior**	40 %	65 %
• **Outside**	0 %	65 %

Lunawood estimated that 40% of the ThermoWood® panels used indoors in the German market could be recycled or reused. The interior panel could be completely recycled if only there was a contractor and a variety of uses. Exterior panels can also be utilized, but the most practical way is to use in energy production. If wood chips will be made it needs again a contractor to remove the screws needed to install the panel. In Germany, there is a desire to increase the re-use of wood before burning it. Lunawood ThermoWood® is well suited for re-use when only other boundary conditions are met.

The United Kingdom (UK)

In the UK according to the Industrial and Clean Growth Strategies, the goal is to double resource productivity and eliminate avoidable waste by 2050. There are also many operators in the UK who collect waste and sort it. Woodrecyclers is one of the operators that collects wood waste. It states that 1 332 000 tonnes of wood waste have been recycled, 2 475 000 tonnes of waste are used for biomass energy production and 92 000 tonnes of wood waste have been exported, such as wood chips for energy production. In 2018, 222.2 million tons of waste was generated in the UK, of which 1.8% was wood waste. (UK Gov, 2022).

In England, the household recycling rate was 44.0% compared with 49.1% in Northern Ireland, 41.0% in Scotland and 56.5% in Wales (UK Gow, 2022). Table 16 provides estimates of how ThermoWood® is utilized in the UK based on data from Lunawood and UK Gov (2022). Table 16 shows estimation of reuse of ThermoWood® in the UK.

Table 16. Estimation of reuse of ThermoWood® in the UK.

	UK	
Reuse	evaluation by Lunawood	estimation based on UK Gov (2022)
Interior	40 %	44 %
Outside	0 %	

Lunawood estimated that 40% of the ThermoWood® panels used indoors in the UK market could be recycled or reused. The interior panel could be completely recycled if only there was a contractor and a variety of uses. Exterior panels can also be utilized, such as wood chips, but this again requires a contractor to remove the screws needed to install the panel. The recycling rate of households is based on data provided by the UK Gov (2022).

USA

In the USA, reducing consumption and reuse of waste / by-products is also a priority. After reducing consumption, the goal is to recycle and compost. Then utilize the side streams for energy production. The rest of the waste streams, which cannot even be used for energy production, are treated and taken to landfill. Waste management of municipal solid waste, which includes recycling, composting, combustion with energy recovery and landfilling processes will continue to be a high priority for states and local governments waste management hierarchies (EPA, 2021a).

The recycling and reuse sector had 681,000 jobs and salaries were paid $ 37.8 billion (EPA, 2021 b). In 2018, 292.4 million tonnes (US short tonness, unless specified) of municipal solid waste (MSW) was generated in the US, equivalent to 4.9 pounds = 2.22 kg per person per day. The volume of MSW increased from 2017 to approximately 23.7 M tons. About 69 million tonnes of municipal solid waste was recycled and 25 million tonnes were composted. The combined share of recycling and composting was 32.1%. Of MSW's total volume, 6.19% was wood waste equivalent to 18 090 000 tonnes. About 3 100 000 tonnes (4.49%) of wood waste was recycled and 12 150 000 tonnes (8.32 %) were disposed of in landfills (EPA, 2021a). Table 17 shows the recycling rate of wood waste in the United States.

Table 17. Estimation by Lunawood how much interior and exterior glading is reused and recycling rate of wood in the USA (EPA, 2021 a).

	USA	
Reuse	evaluation by Lunawood	evaluation based on EPA's research (EPA, 2021 a)
Interior	40 %	4.49 %
Outside	0 %	

Lunawood estimated that 40% of the ThermoWood® panels used indoors in the USA market could be recycled or reused. The interior panel could be completely recycled if only there was a contractor and a variety of uses. Exterior panels can also be utilized, such as wood chips, but this again requires a contractor to remove the screws needed to install the panel.

South Africa

According to the waste classification, wood waste is found in two places in South Africa: among organic waste and in construction and demolition (C&D) waste. These waste categories fall under the General waste classification. Organic waste also includes agricultural, horticultural and kitchen waste. Among the construction waste there are e.g. plastic, paper, roofing, stones, earth and wood, which account for the largest share of C&D waste, about 27%. There are less statistics on the reuse of C&D waste. C&D waste is sorted at its place of origin. C&D waste is used in landfill structures, then it is possible to get a discount on gate fees or no need to pay them at all. Wood-based waste classified as organic waste comes from sawmills. Sawmill production produces sawdust (20%), wood chips (19%) and bark (9%) and 52% lumber. An estimated 72 sawmills use 5.2 Mt of wood. Thus, 990 400 tons of wood chip, 369 000 tons of bark and 1 MB of sawdust has been generated. The paper and pulp industry generates 245 219 t of bark. (Waste report SA, 2018).

In South Africa, it is estimated that 108 million tonnes of waste were generated in 2011, of which 98 million tonnes ended up in landfills. Thus, the recycling rate was only 10%. In the general waste category, about 20.7 Mt is recycled, while about 54.2 Mt is generated. Thus, the recycling rate is 38.3%. Little data is available on the recycling and recovery of C&D waste. Approximately 4.5 Mt / year of C&D waste is generated annually. Wood accounts for 1 125 000 tonnes (27%) of recycled C&D waste (Waste report SA, 2018). Table 18 provides an estimate of the percentage of wood waste recycled and CompanyX's own estimate of how much ThermoWood® would be recycled in South Africa (Waste report SA, 2018).

Table 18. Estimation of reused rates of ThermoWood® by Lunawood and recycling rate in South Africa by Waste report SA (2018).

South Africa		
Reuse	evaluation by Lunawood	evaluation based on (Waste report SA, 2018).
Interior	40 %	recycling rate 27 %
Outside	0 %	

Lunawood estimated that 40% of the ThermoWood® panels used indoors in the South Africa market could be recycled or reused. The interior panel could be completely recycled if only there was a contractor and a variety of uses. Exterior panels can also be utilized, such as wood chips, but this again requires a contractor to remove the screws needed to install the panel.

6.2.10 Energy yield from 100 m^3 of ThermoWood® in selected market areas

For the carbon footprint of thermally modified wood, an estimate was made of how much energy is produced per 100 m^3 in selected market areas. The assessment shows how much wood or wood-based products are used in energy production. How much energy is obtained from thermally modified wood is estimated by how much wood is recycled in the selected countries. The wood recycling percentage is used to calculate how much 100 m3 of thermally modified wood can be used for energy production. The m^3 have been changed to correspond to MWh.

Germany

There are several operators in Germany who use wood for their energy production. According to the German Waste Management Legislation, companies in Germany should re-use more waste and avoid waste generation than dispose of waste in landfills (Garcia and Hora, 2017). The reported values for wood-based fuel use are most often included in full in the category biomass. In 2021, 77% of the heat produced by biomass in Germany (171 billion kWh) was solid biomass, mainly wood or other wood products. Thus, 132 billion kWh of heat was produced with wood-based products. Households use wood or wood-based products, including pellets, with heat production in 2021 of 81 130 GWh, which is 6.7% more than in 2020. Heat was also produced from biogas and biomethane (17.4 billion kWh), biogenic waste (15.9 billion kWh) and liquid biomass (2.9 billion kWh) (Umwelt Bundesamt, 2022). Table 19 shows Lunawood's estimate of how much recycled wood or wood-based products is used for combustion, and the amount of heat produced in Germany by wood or wood-based products based on data provided by Umwelt Bundesamt (2022) and the Fachagentur Nachwachsende Rohstoffe e. V. (FNR, 2020).

Table 19. Estimate of how much heat is produced from recycled thermally modified wood by Lunawood and heat production from wood or wood-based products in Germany by Umwelt Budesamt (2022) and Fachagentur Nachwachsende Rohstoffe e. V. (FNR) (2020).

Germany **Energy production from wood or wood-based products**		
	estimated by Lunawood	Umwelt Bundesamt (2022) and FNR (2020)
Wood from interior	60 %	depend on reference estimation of the share of wood or wood-based products is 53.6 % - 77% from biomass, average 65.3 %
Wood from outside	100 %	

The report by the Fachagentur Nachwachsende Rohstoffe e. V. (FNR) points out that in 2018, primary energy consumption in Germany was 12,963 PJ, of which renewable energy accounted for 14.0%. Of this, 7.5% came from biomass, accounting for 53.6% of renewable energy. On the other hand, the Umwelt Bundesamt, (2022) states in its report that 77% of biomass is wood or wood-based products. Due to various sources, I estimate that about 65.3% of wood or wood-based by-products are utilized in energy production. Table 23 summarizes the energy yield of 100 m^3 of wood or wood-based product in selected market areas.

The United Kingdom (UK)

In 2020, 24.3 million tonnes of oil equilevant (282 609 000 MWh) of renewable energy as a primary energy was used in the UK, of which 18.1 million tonnes of oil equilevant (210 503 000 MWh) was produced electricity and 4.5 million tonnes of oil equilevant (52 335 000 MWh) for heat and 1.6 million tonnes of oil equilevant (18 608 000 MWh) in transport. Renewable energy was produced by wood with 1 115 000 tonnes of oil equivalent (12 967 450 MWh) (UK Energy). According to the UK Energy in Brief 2021 report, of the renewable energy used as a primary energy source, 4.57% is wood. The share of wood in electricity and heat produced with renewable energy is 4.24%.

In the UK 10 % of UK total energy consumption was generated by renewable and waste energy sources in 2017 (Office for National Statistics). Table 20 shows how much energy from wood is produced in the UK (UK Energy) and Lunawood's own estimate of how much interior and exterior cladding would be used to produce heat.

Table 20. Estimate of how much heat is produced from recycled thermally modified wood by Lunawood and heat production from wood products in the UK by UK Energy in Brief (UK Energy).

UK Energy production from wood		
	estimated by Lunawood	UK Energy
Wood from interior	60 %	4.25 % of renewable energy production (heat and electricity) is produced by wood
Wood from outside	100 %	

UK uses 60% of available biomass for electricity production. The largest source of biomass is wood pellets. In 2018, it was estimated that 7.2 million tonnes of wood pellets were used to generate electricity. (Office for National Statistics)

USA

In 2021, about 2.1% of total U.S. energy consumption was produced by wood and wood waste, such as bark, sawdust, wood ships, wood scrap and paper mill residues. The wood product and paper industry use wood and/or wood waste the most in their energy production. The share of energy produced from wood and wood waste in industry is 5.2% annually. 4.0% of the energy consumption of housing was produced from wood (EIA, 2022). MSW collected in 2018 was 11% or 34.6 million tonnes, of which 2 840 000 tonnes or 8.22% was wood (EPA2021a). Table 21 shows estimate from Lunawood how much thermally modified wood will be used for energy production and the share of energy production utilized from wood containing in MSW in the USA in 2021.

Table 21. Estimate of how much heat is produced from recycled thermally modified wood by Lunawood and energy production of wood from municipal solid waste (MSW) in the USA by EIA (EIA, 2022).

USA **Energy production from wood**		
	estimated by Lunawood	EIA, 2022
Wood from interior	60 %	2.1 %
Wood from outside	100 %	

In the USA in 2021, 2.1 quadrillion BTUs (British Termal Units) of renewable energy were wood and wood-derived fuels. This corresponds to 65190 MWh (1 BTU = 0.00000029 MWh) (EIA b, 2022). Wood is used as an energy source mostly in the sawmill industry, all wood is used for goods. This amount of energy corresponds to about 180 000 000 tons of wood (Forest2market).

South Africa

In Africa woody biomass in a form of woodfuel and charcoal have the important role in the energy mix in Africa. Over 48% of the total primary energy supply is biomass. Woodfuel contains most of firewood, which represents the largest share in wood energy fuels production and consumption. It has traditionally been used mostly in household energy production. Worldwide, wood fuels account for 34% of energy production used in cooking. More than 82% of the energy in African households is produced from wood. What fuels are used in energy production also depends on the price of energy and also the wealth of households (UNEP 2019).

In South Africa, which is classified as an urban area on the African continent, there is more coal used for energy production than in rural areas, where energy is produced from biofuels. Forests or forest-like areas cover 35% of South Africa's land area. In 2015, 12 313 862 m^3 of woodfuel was used in South Africa (UNEP 2019). In South Africa, attention has been paid to the use of renewable energy and its utilization. For example, various investment programs are used to attract foreign investors. According to the new regulations, an additional 14 725 MWh of bioenergy should come to South Africa, of which 210 MWh would be produced from biomass. At present, 35 669 GWh of bioenergy has already been produced through various investment programs (Department of Environmental Affairs, 2018). Table 22 shows estimate from Lunawood how much thermally modified wood will be used for energy production and the share of energy produced from wood in the South Africa.

Table 22. Estimate of how much heat is produced from recycled thermally modified wood by Lunawood and energy yield from wood or wood-based fuel (UNEP 2019).

South Africa **Energy production from wood**		
	estimated by Lunawood	UNEP, 2019**
	60 %	0.80 MWh/m^3 * 12 313 862 m^3 = 9 851 090 MWh
Wood from outside	100 %	

*Conversion is based on Lauhanen et al. (2014)

**no percentages were found for the use of wood in energy production

UNEP (2019) states in its report that 12 313 862 m^3 of woodfuel was used, which was converted to MWh. This is the amount of wood and wood-based fuels used in household energy production (UNEP 2019). The sawmills and the paper and pulp industry generate fractions that are utilized in industrial energy production (Waste report SA, 2018).

6.2.11 Wood as an energy source in selected markets

Table 23 estimates how much energy can be produced per 100 m^3 of recycled thermally modified wood or wood-based products. The amount of thermally modified wood used for energy productions varies because the wood recycling rate associated with selected countries varies. The chapter 6.2.9 describes how the recycling rate has been determined in the selected target countries. Cubic meters (m^3) are converted to MWh (Lauhanen et al., 2014) to see how much energy can be produced.

Each selected target country has its own waste management and policies. In Germany, the EU waste hierarchy is followed (Renewable Energy Act and Waste Management Directive). Although the UK (UK Energy) is no longer a member of the European Union, there is also a similar waste hierarchy as in Germany. The USA (EIA, 2022) follows the same waste hierarchy as in Europe. In South Africa, the focus is on developing waste management, which also requires a lot of investment (Waste report SA, 2018).

Recycled wood is often made into wood chips. The UK exports a lot of wood chips abroad. The global warming potential (GWP) of woodchip production is 17 kg CO2 eq/m^3 including fuel supply and combustion ((Bates & Henry, 2009).

Table 23. Estimate of energy production from wood or wood-based products in selected market areas and global warming potential of producing wood chips (Bates & Henry, 2009). Table summarize waste hierarchy and policies (Renewable Energy Act and Waste Management Directive; UK Energy; EIA (2022); Waste report SA (2018)).

Selected market area	**Energy from 100 m^3 of thermally modified timber**	**GWP [kg CO_2 eq/m^3] of wood chip production**	**Waste hierarchy**	**Policy**
Germany	$=0.653*100\ m^3$ $= 65.3\ m^3$ converted to MWh $=65.3\ m^3 * 0.80\ MWh/m^3$ $= 52.24$ MWh*		Reduce, recycling and re-use are more important options than energy production	Renewable Energy Act and Waste Management Directive
UK	$=0.24*100\ m^3$ $= 24.0\ m^3$ converted to MWh $= 24.0\ m^3 * 0.80\ MWh/m^3$ $= 19.2$ MWh*	17 including fuel supply and combustion (Bates & Henry, 2009)**	Reduce, recycling and re-use are more important options than energy production	UK Energy
USA	$=0.021*100\ m^3$ $=2.1\ m^3$ converted to MWh $=2.1\ m^3 * 0.80\ MWh/m^3$ $= 1.68$ MWh*		Reduce, recycling and re-use are more important options than energy production	EIA, 2022
South Africa	$=0.27*100m^3$ $=27.0\ m^3$ converted to MWh $=27.0\ m^3 * 0.80\ MWh/m^3$ $= 21.6$ MWh*		Improvement of waste management processes and investments are needed	Waste report SA, 2018

*Conversion is based on Lauhanen et al. (2014)
** includes biogenic carbon

Based on this estimate a number of different sources related to selected market areas, Germany produces the most energy per 100 m^3 of recycled thermally modified wood, followed by England, South Africa and the USA.

6.3 Carbon footprint of waste management

In the total carbon footprint, using the cradle-to-grave approach, the GWP of waste management has also been taken into account in the selected countries. Greenhouse gas emissions related to Municipal solid waste (MSW) management were found in the literature. MSW includes organic waste, including wood and wood-based waste. Mühle et al. (2010) compared the greenhouse gas emissions of German and UK MSW waste management, which were 34 kg CO_2 eq/ton = 0.034 kg CO_2 eq/kg and 175 kg CO_2 eq/ton = 0.175 kg CO_2 eq/kg, respectively. Although Germany and England are European countries, the results are still different, because in Germany the recycling percentage is higher and a lot of energy is made from waste there. In England, the recycling percentage is lower and a lot of waste is sent to the landfill there (Mühle et al., 2010). In the USA, the greenhouse gas emissions of landfill organic waste about 400 kg CO_2 eq/ton, i.e. 0.4 kg CO_2 eq/kg (Nordahl et al., 2020). In South Africa, the average greenhouse gas emission from composting wet garden waste is 179 kg CO_2 eq/ton, i.e. 0.179 kg CO_2 eq/kg (Friedrich, E., 2013).

7 Results

In this work, the impacts during the product's life cycle were studied using the carbon footprint which were completed (table 24) for the Finnish thermally modified wood manufacturers (called Lunawood) planed thermally modified wood products and thermotimber using the cradle-to-grave approach. The carbon footprint calculation took into account harvesting, sawing boards, producing ThermoWood®, transportation up to endusers and recycling potential and disposal phase. Four market areas where thermally modified wood is sold were selected for this study: Germany, UK, USA and South Africa. CO_2 emissions from recycling and final disposal were analyzed using data found in various reports and articles. The carbon footprint was changed to correspond to CO_2 emissions per square meter, which was used to compare how CO_2 emissions are distributed when using different service life lengths and square meters.

The carbon footprint study calculates the potential impact of the product on global warming over the entire life cycle, taking into account the limitations made in the selected processes. The unit used is carbon dioxide equivalent (CO_2e).

Table 24 Summary of carbon footprints [kg CO_2 eq/m^3] in selected market areas using cradle-to-grave approach.

Market area	**kg CO_2 eq/m^3**
Germany	247
UK	294
USA	420
South Africa	278

These results are presented in more detail in sections 7.3.1 – 7.3.4.

7.1 Data collection and calculation methodology of carbon footprint of thermally modified wood using from cradle-to-grave approach

The carbon footprint of the production was calculated in such a way that the Lunawood's carbon footprint of both mills was calculated separately for the thermally modified wood and the agreed planed products, after which the average carbon footprint weighted by the amount of production was calculated.

When the planing was done by a subcontractor, the EPD of sawn timber made by Sahateollisuus ry was used for CO_2 emissions (RTS_124_21). The CO_2 emission caused by Lunawood's own planing has not been specified. This is because the Lunawood has not specified the electricity consumption of the devices or other accessories per device.

In the following chapters the results of carbon footprint of planed ThermoWood® and thermotimber using cradle-to-grave approach, allocation that have been taken into account and utilization of wood waste as wood chips are presented. Recycling and disposal emissions were related to the m^3 quantities that Lunawood exports to each selected country. The greenhouse gas emissions of different activities needed for ThermoWood® manufacturing process is indicated as percentages compared to the total greenhouse gas emissions of thermally modified wood in each selected country. This is why harvesting, energy including electricity, planning, waste management, other, CO_2 emissions released from one m^2 show different percentages, even though the carbon footprint of harvesting, production and planing are the same for all products that are exported around the world. Transport emissions, emissions divided per different lengths of service lifes, recycling and disposal emissions differ by country. In Appendix 1, emissions related to transport to selected market areas are presented in more detail. Carbon footprint of transportation includes wood transportation to sawmill and to further processing, fuel transportation, transportation for items needed in packaging and transportation to end-user.

7.2 Effects of service life and square meters on carbon dioxide emissions of thermally modified wood

The effects on the amount of greenhouse gases were investigated by comparing the service lives of planed and thermotimber of different lengths to each other in outdoor and indoor and different square meter quantities. The carbon footprint [kg CO_2 eq/m^3] was converted to [kg CO_2 eq/m^2] and it was calculated how much greenhouse gases were generated in the production of different square meters. When the carbon dioxide emission per square meter was calculated, the process flows affecting the product until the disposal were taken into account. Table 24 shows the process flows that were taken into account when calculating the carbon dioxide emissions during service life per square meter in different market areas.

Table 24. Process units that have been considered when the CO_2 emissions of ThermoWood® during service life have been defined.

Process flows	**Thermotimber**	**Planed ThermoWood®**
Harvesting	X	X
Productions including energy, transportation in Finland, waste management, other supplies that are needed	X	X
Planing		X
Transportation to producer's customer	X	X
Transportation to enduser	X	X

Carbon dioxide emissions during life cycle are affected by transportation to the market area and the journey to the end user, as well as the production of thermally modified wood, as well as the length of service life and the size of the thermally modified wood surface. The number of cubes per square meter of different planed products varies. The longer the service life is, the less emissions are generated per year.

Thermotimber's carbon footprint is smaller than planed thermally modified wood, because thermotimber is not planed. The carbon footprint caused by planing is different if the planing takes place at Lunawood's mill or as a subcontractor. The carbon footprint of subcontracted planing is 34.5 kg CO_2 eq/m^3 (RTS_124_21, 2021). The greenhouse gas emission caused by the planing at Lunawood is 22.4 kg CO_2 eq/m^3 (this study). The carbon footprint of subcontracted planing is 35 % larger than the carbon footprint of Lunawood's inhouse planing.

In the following figures 14 – 17 the carbon footprint per cubic meter has been changed by Lunawood's factor to correspond to CO_2 emissions per square meter. This describes how much CO_2 emissions are generated in the production of one square meter.

7.2.1 Carbon footprint using cradle-to-grave approach for exported ThermoWood® to Germany

Figure14 shows the percentages of the carbon footprint of the different functions of the planed thermal wood delivered to Germany in relation to the total cradle-to-grave carbon footprint in this option. The total emission is 247 kg CO_2 eq/m^3. The emissions caused by transportation have been added together, which includes transportation in Finland and transportation to Lunawood's customer in Germany and from there to the end user. The average distance to the end user is 250 km, estimated by Klöpferholz. Transportation accounts for 44 % of all emissions, energy accounts for 21 % and harvesting accounts for 13 %. Planing accounts for 9 % of total emissions. Carbon footprint of transportation includes wood transportation to sawmill and to further processing, fuel transportation, transportation for items needed in packaging and transportation to end-user.

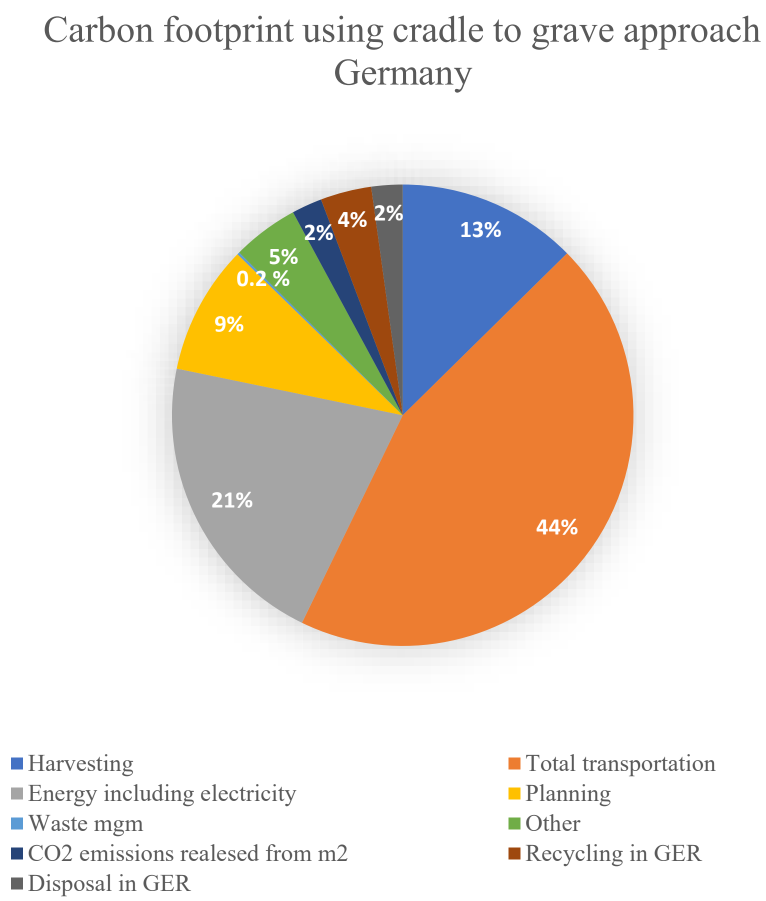


Figure 14. Finnish ThermoWood® producer's carbon footprint of planed ThermoWood® to German market using cradle-to-grave approach. Energy including energy refers to manufacturing of planed ThermoWood®. CO_2 emissions per m^2 correspond to the emissions of one m^3 of CO_2.

When thermotimber is exported to Germany and deliver it to the end user, the total carbon footprint is 9% lower compared to the planed ThermoWood® carbon footprint for that market. The difference is that planing requires more energy.

7.2.2 Carbon footprint using cradle-to-grave approach for exported ThermoWood® to UK

In figure 15 shows the percentages of the carbon footprint of the different functions of the planed thermally modified wood delivered to the UK in relation to the total cradle-to-grave carbon footprint in this option. The total emission is 294 kg CO_2 eq/m^3. The emissions caused by transport have been sum up, which includes transport in Finland and transport to Luanwood's customer in the UK and from there to the end user. The average distance to the end user is 150 km, which is estimated by Lunaood's promoter UK. Transportation accounts for 41% of all emissions, energy accounts for 18% and harvesting accounts for 11%. Planing accounts for 7% of total emissions.

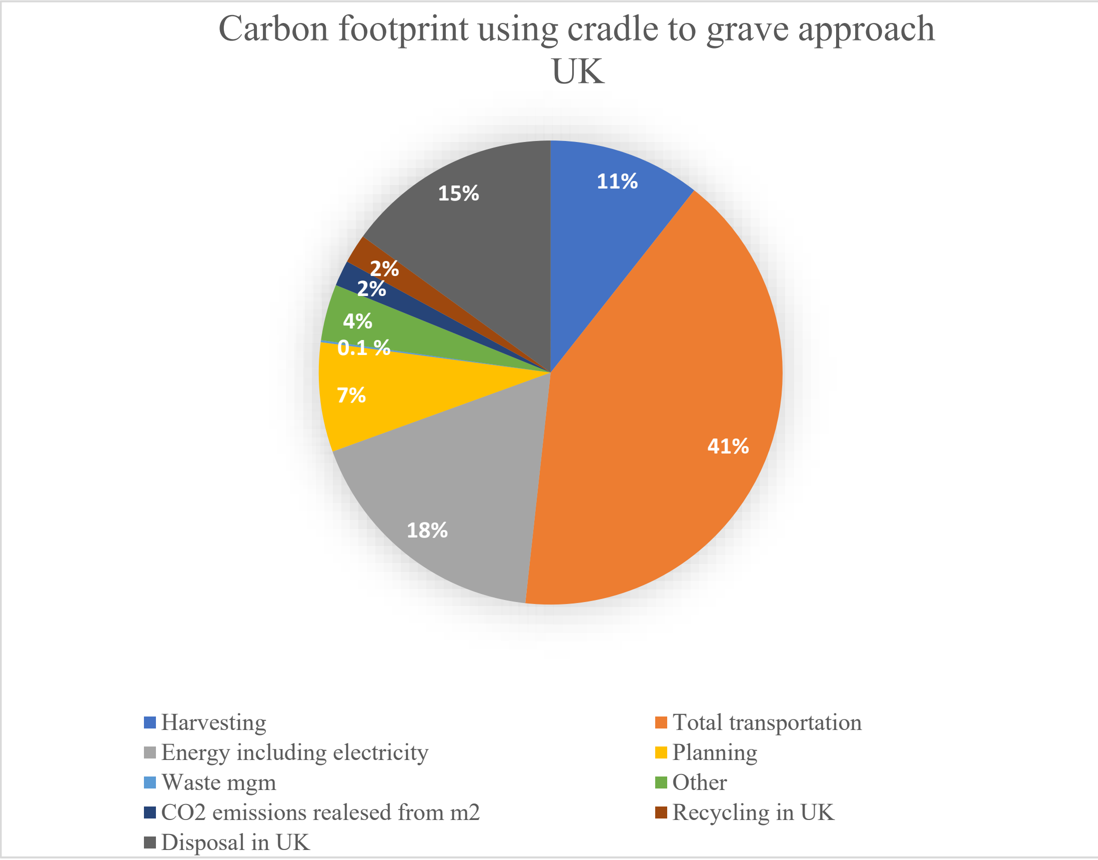


Figure 15. Finnish ThermoWood® producer's carbon footprint of planed ThermoWood® to UK market using cradle-to-grave approach. Energy including energy refers to manufacturing of planed ThermoWood®. CO_2 emissions per m^2 correspond to the emissions of one m^3 of CO_2.

When thermotimber is exported to UK and delivered to the end user, the total carbon footprint is 7% lower compared to the planed ThermoWood® carbon footprint for that market. The CO_2 emissions of the disposal phase are higher than in Germany, because recycling works less well than in Germany. In this case, more wood goes to the landfill, and it does not end up being used again nor for energy production.

7.2.3 Carbon footprint using cradle-to-grave approach for exported ThermoWood® to the USA

In figure 16 shows all the emissions that affect the carbon footprint of planed thermally modified wood when it is sold to the end user in the USA in relation to the total cradle-to-grave carbon footprint in this option. The total emission is 420 kg CO_2 eq/m^3. The emissions caused by transportation have been summed up, which includes transportation in Finland and transportation to Lunawood's customer in the USA and from there to the end user. The average distance for the end user is 500 km, which has been estimated by Lunawood's salesperson in the USA. The estimate is based on long distances within states. Transportation accounts for 30 % of all emissions, energy accounts for 12 % and harvesting accounts for 8 %. Planing accounts for 5 % of the total emissions of this option. In the USA, the largest emission from the total carbon footprint is generated by municipal solid waste management at the landfill. This also means that the recycling rate is very low.

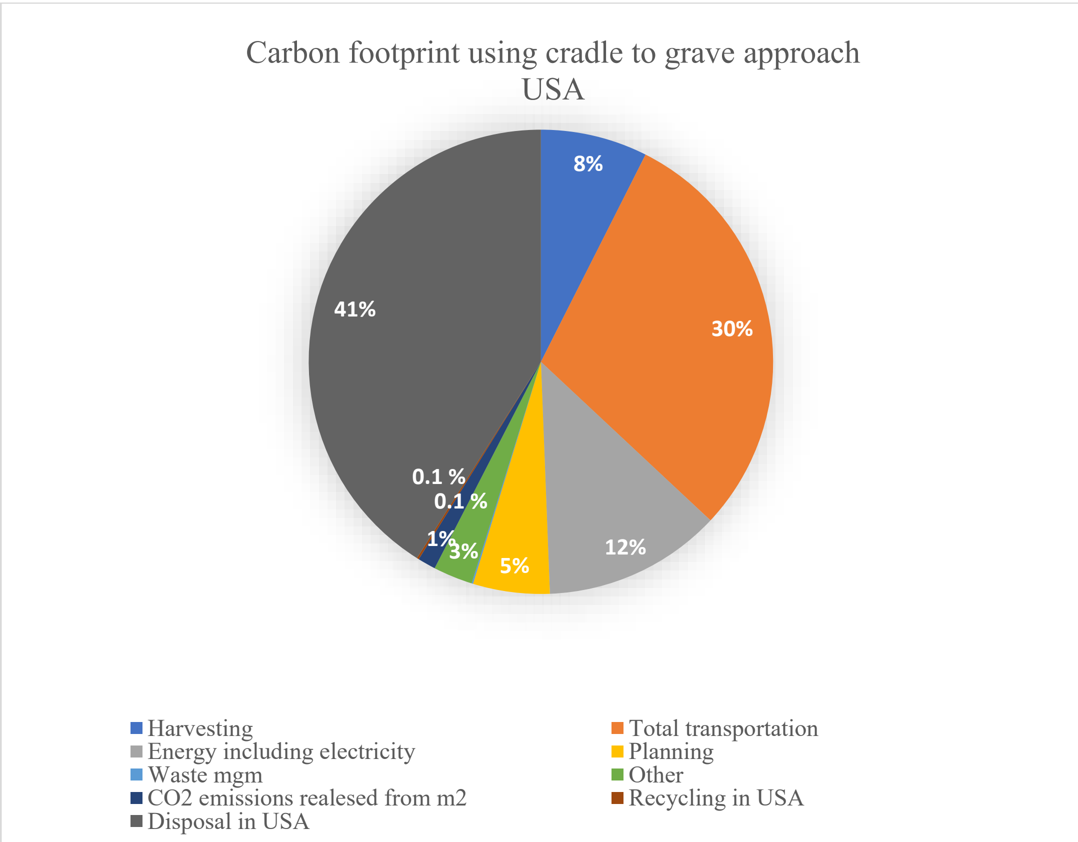


Figure 16. Finnish ThermoWood® producer's carbon footprint of planed ThermoWood® to USA market using cradle-to-grave approach. Energy including energy refers to manufacturing of planed ThermoWood®. CO_2 emissions per m^2 correspond to the emissions of one m^3 of CO_2.

When thermotimber is exported to the USA and deliver it to the end user, the total carbon footprint is 5% lower compared to the planed ThermoWood® carbon footprint for that market. In the USA recycling rate is really low compared to European countries: Germany and the UK. A lot of wood in the USA goes to landfills, so its utilization is minimal.

7.2.4 Carbon footprint using cradle-to-grave approach for exported ThermoWood® to South Africa

Figure 17 shows all the emissions that contribute to the carbon footprint of planed thermally modified wood relative to the total cradle-to-grave carbon footprint in this option when it is sold in South Africa to the end user. The total emission is 278 kg CO_2 eq/m^3. The emissions caused by transportation have been added up, which includes transportation in Finland and transportation to Lunawood's customer in South Africa and from there to the end user. The average distance for the end user is 600 km, which is estimated by Lunawood. Transportation accounts for 44 % of all emissions, energy accounts for 19 % and harvesting accounts for 11 %. Planing accounts for 8 % of total emissions

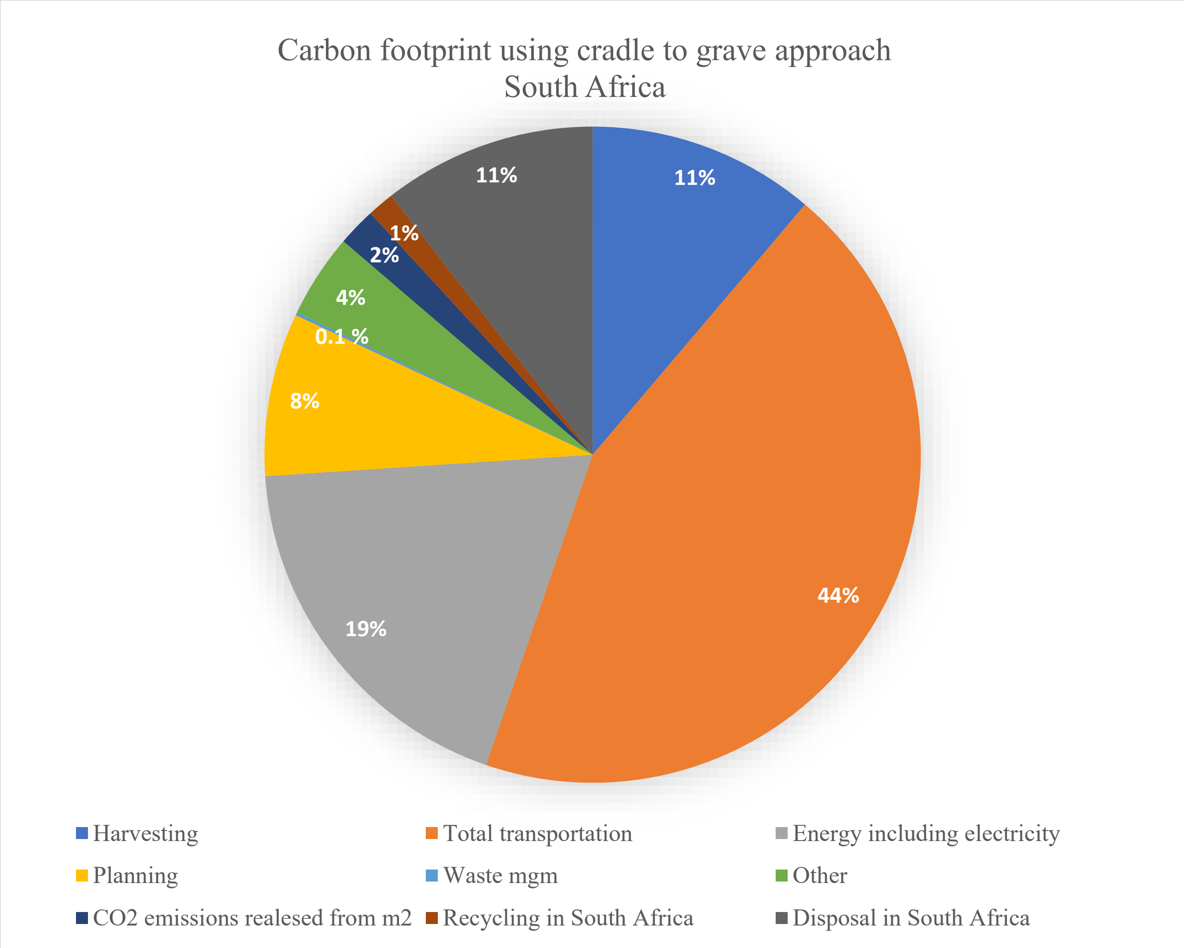


Figure 17. Finnish ThermoWood® producer's carbon footprint of planed ThermoWood® to South Africa market using cradle-to-grave approach. Energy including energy refers to manufacturing of planed ThermoWood®. CO_2 emissions per m^2 correspond to the emissions of one m^3 of CO_2.

When thermotimber is exported to South Africa and delivered to the end user, the total carbon footprint is 8 % lower compared to the planed ThermoWood® carbon footprint for that market. In South Africa, wood is used as woodfuel for heating and cooking.

7.3 Greenhouse gas emissions of recycling and disposal in selected countries

The greenhouse gas emissions of recycling and disposal of thermally modified wood produced by Lunawood have been estimated based on the values found in the literature. Recycling and emissions from waste management were evaluated, how much wood and wood-based waste is recycled in the selected countries and how much ends up in landfill.

Table 25 shows the recycling percentage of wood and wood-based waste in selected countries and the greenhouse gas emissions from woodchip production and the greenhouse emissions caused by municipal solid waste management.

Table 25. Recycling rate and greenhouse gas emissions of municipal solid waste management of Germany, UK, USA and South Africa and greenhouse gas emission of production of wood chips.

	Recycling rate [%]	Reference	GHG emissions of wood chip production [kg CO_2 e/m^3]	Reference	GHG emissions of MSW management [kg CO_2 eq/ton]	Reference
Germany	65	Garcia & Hora (2017)	17	Bates & Henry, 2009	34	Mühle et al., 2010
UK	44	UK Gov (2022)	17		175	Mühle et al., 2010
USA	4.49	EPA (2021 a)	17		400	Nordahl et al., 2020
South Africa	27	Waste report SA (2018)	17		179	Friedrich, E., 2013

In Germany, the recycling rate is high, so the emissions of wood chips are also higher. In Germany, recycling works the best of these four countries. In the UK, the recycling rate is lower than in Germany. In the USA recycling rate is very low compared to Germany and UK. In South Africa, the recycling rate is six times higher than in the USA. Greenhouse gas emissions from recycling have been calculated taking into account the recycling rate of each country, which is used to calculate how much ThermoWood® is recycled. The recycling rate of ThermoWood® is expected to be the same as the recycling rate of each country shown in table 24. The amount of recycled ThermoWood® in cubes has been converted to MWh using the value of 0.8 MWh/m^3 as a conversion factor (Lauhanen et al., 2014). The values obtained from this have been multiplied by the greenhouse gas emissions of woodchip production [17 kg CO_2 eq/m^3] (Bates & Henry, 2009). It has been assumed that the products of Lunawood would end up in a landfill in the same proportion as other wood and/or wood-based waste ends up in a landfill in each country. Figure 18 shows a comparison of the greenhouse gases [kg CO_2 eq/kg] caused by the recycling and disposal of selected countries.

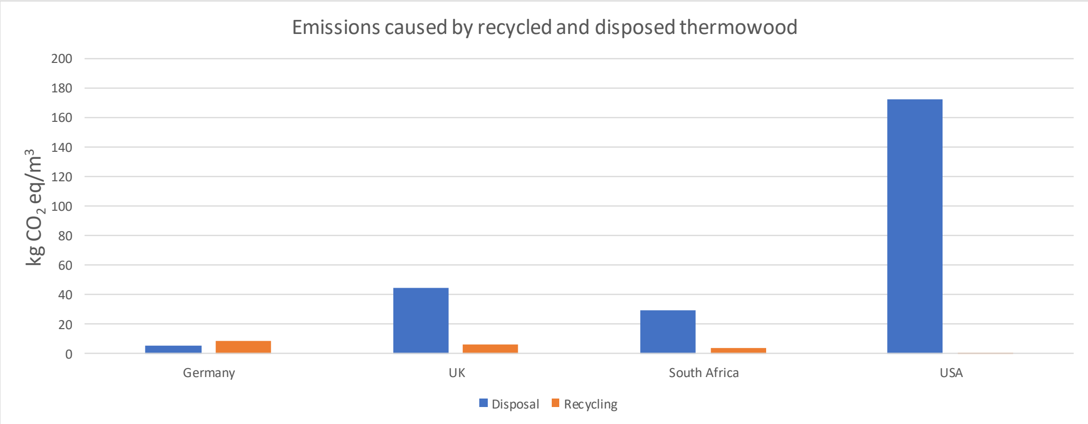


Figure 18 Greenhouse gas emissions caused by recycled and disposed thermally modified wood in Germany, UK, the USA and South Africa.

In Germany, recycling and disposal emissions are very small, while UK and South Africa disposal emissions are greater than the greenhouse gas emissions generated by recycling. Emissions caused by USA disposal are the largest of all, because wood waste is recycled the least. In Germany, wood waste is wanted for reuse or recycling, which can replace virgin wood. Garcia and Hora (2017) estimate that 65 % of wood waste is recycled. In 2016, the UK wood waste is used for e.g. wood chips, which are also exported abroad. In the USA municipal solid waste contains quite amount wood which can be recycled better. In South Africa, there are also more potential to recycle more wood and source separate it from the municipal solid waste streams.

7.4 Greenhouse gas emissions of products from mill in Eastern Finland and Western Finland during their service life

Greenhouse gas emissions from facades are lower with smaller square meters than with large square meters. According to the length of the service life, the amount of emissions decreases as the length of the service life increases. Indoors the expected lifetime is shorter. As the surface area of ThermoWood® increases, the carbon footprint increases. Figures 19-21 show the effect of the length of service life and the number of square meters on the carbon footprint in mill in Eastern Finland.

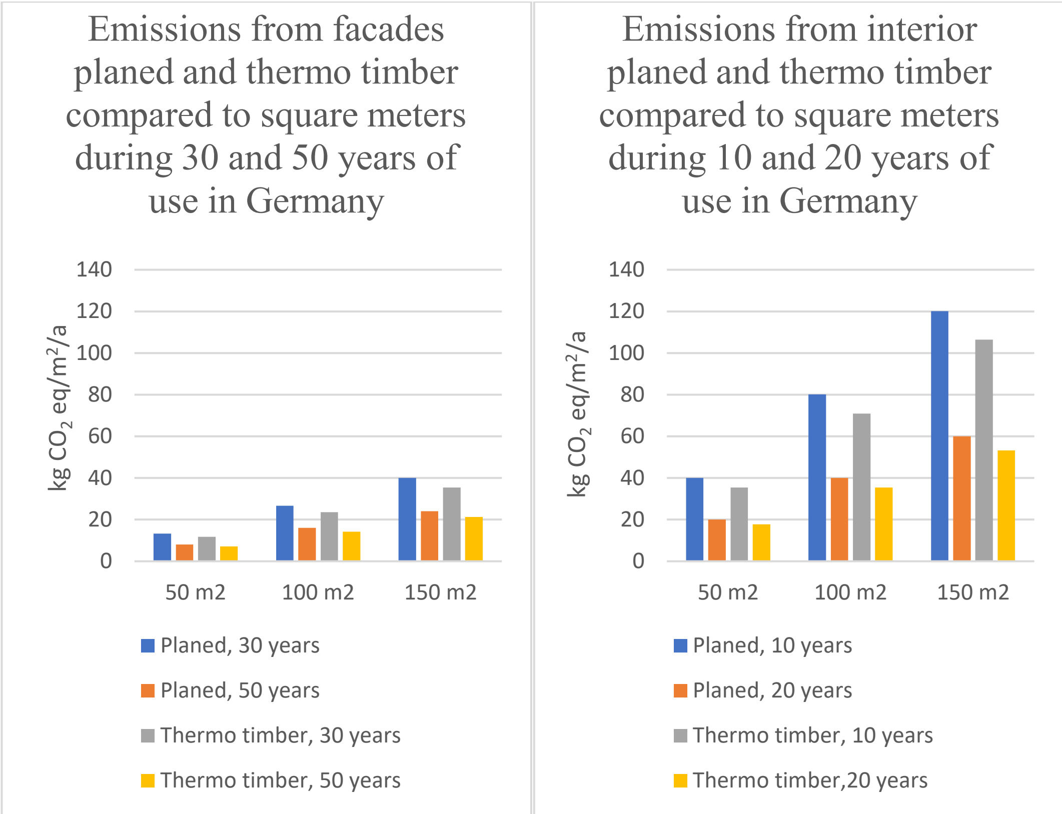


Figure 19. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in Germany.

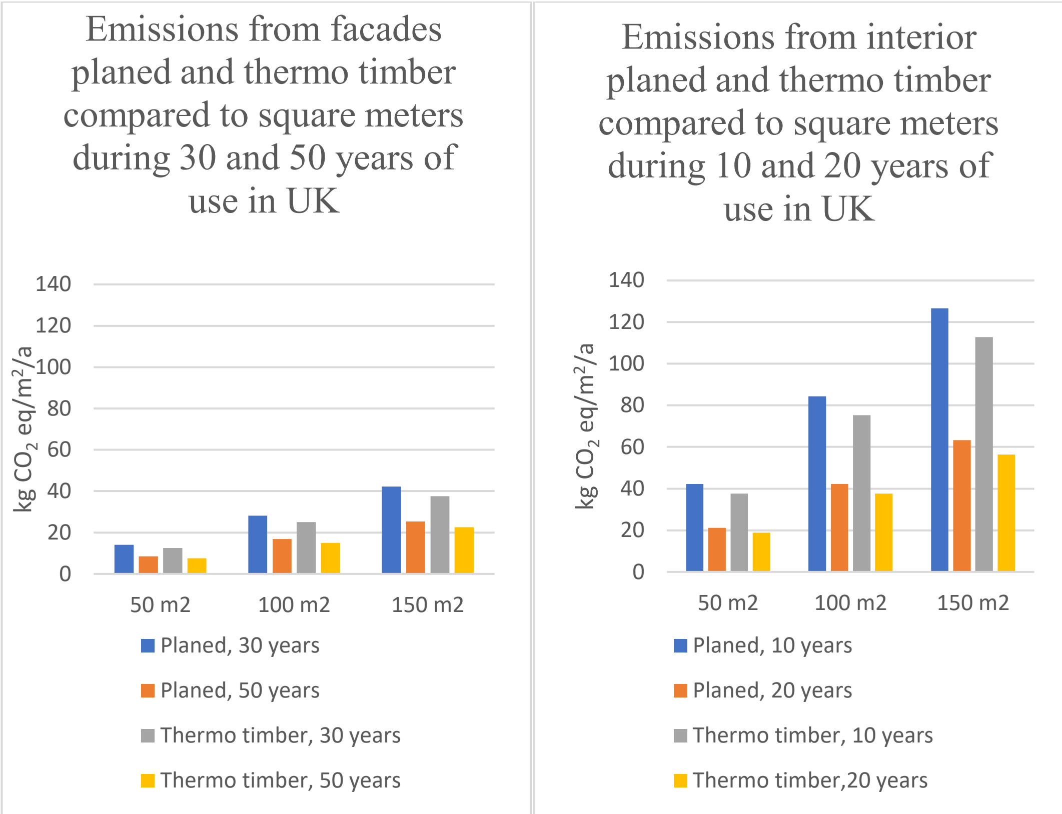


Figure 20. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in UK.

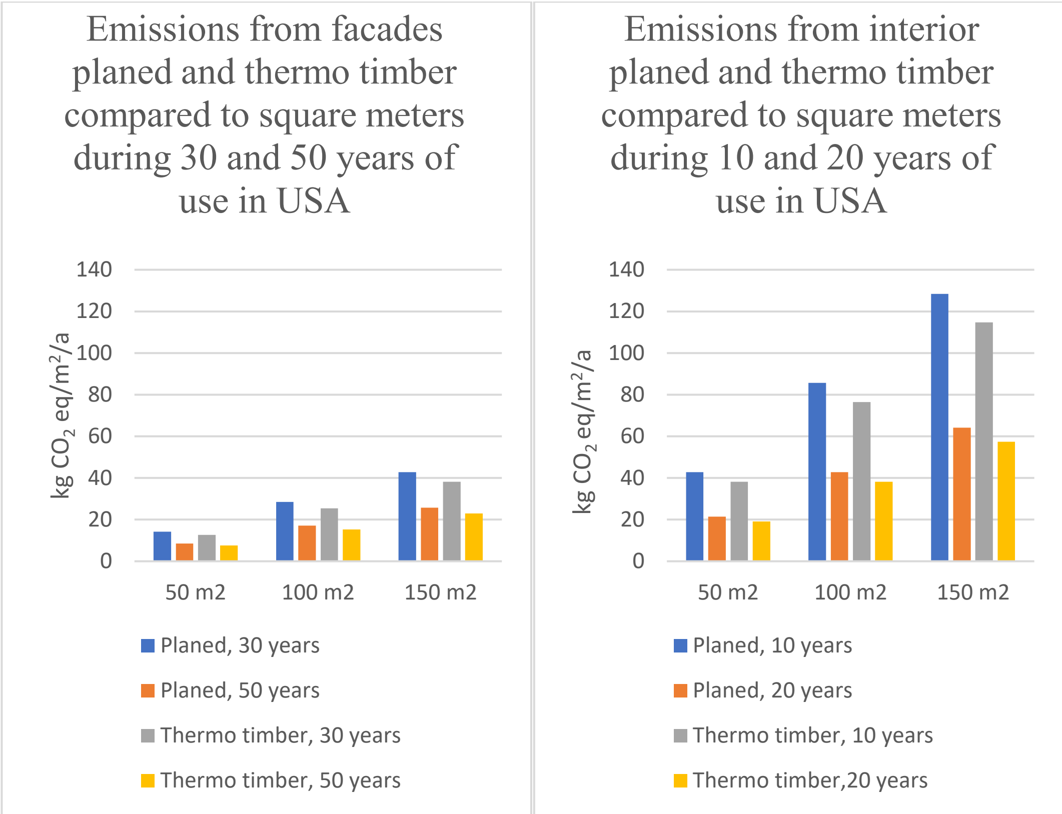


Figure 21. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in USA.

Greenhouse gas emissions related to service life are the lowest in Germany compared to the UK and USA. USA lifetime emissions are the largest.

Figures 22-24 show the effect of length of service life and number of square meters on the carbon footprint in mill in Western Finland.

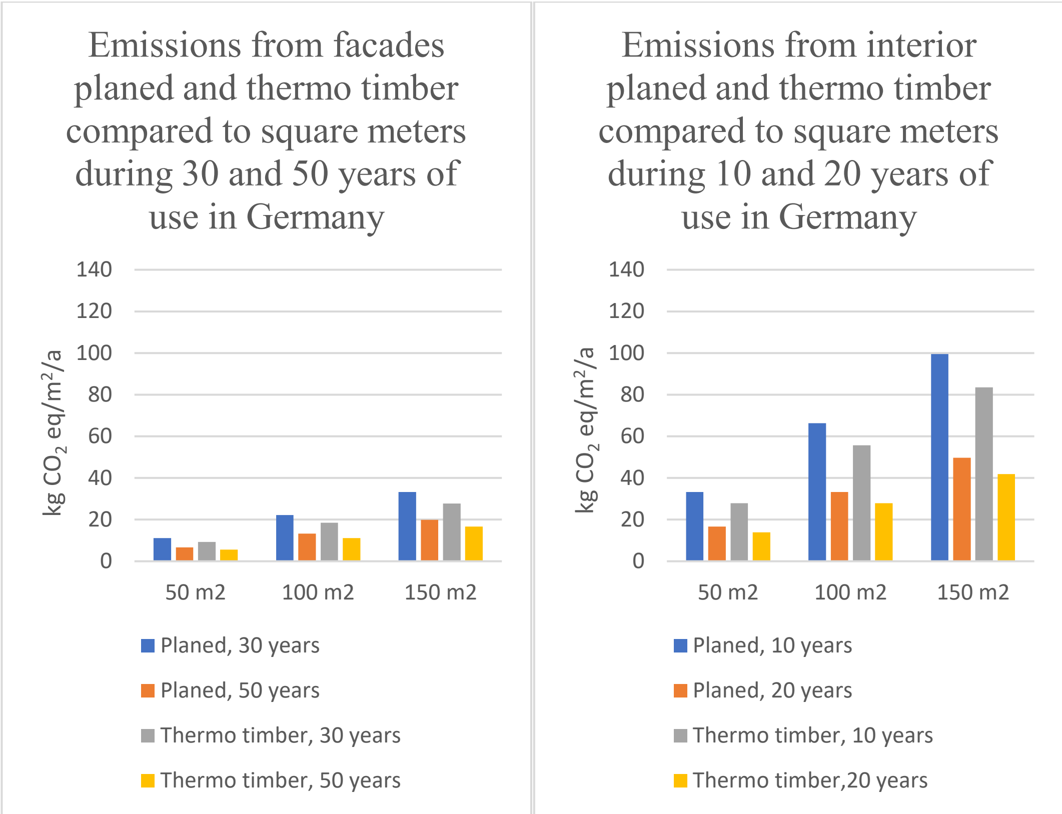


Figure 22. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in Germany.

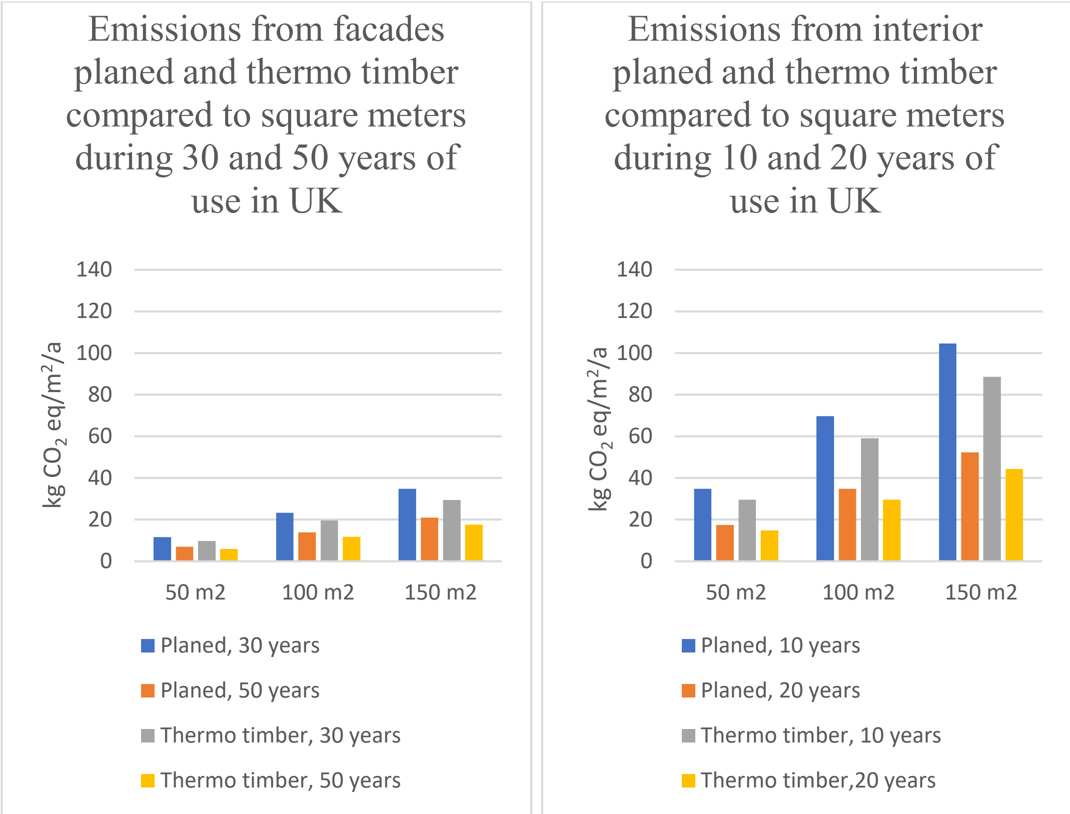


Figure 23. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in UK.

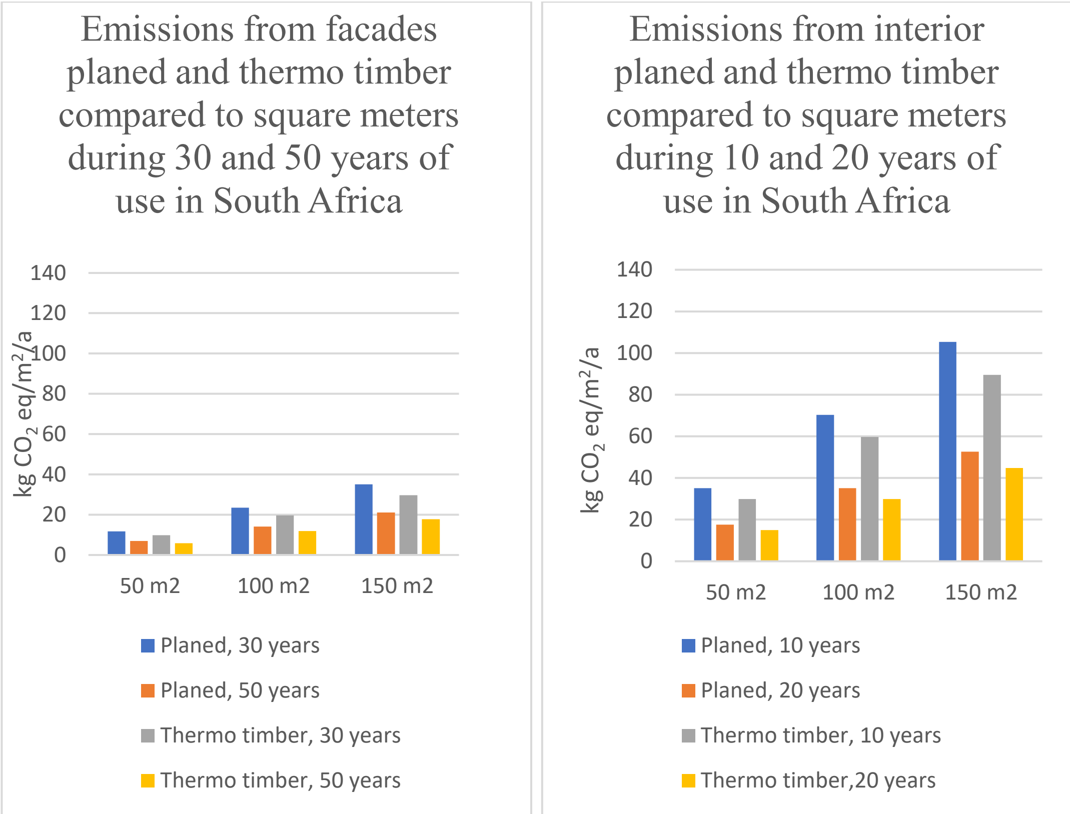


Figure 24. Distribution of greenhause gas emissions from planed and thermotimber of facades and interiors as service lives and square meters increase in South Africa.

Greenhouse gas emissions related to service life are the lowest in Germany compared to the UK and South Africa. UK and South Africa lifetime emissions are almost the same.

7.5 Energy production from 100 m^3 of ThermoWood®

The output of heat production was estimated as how much heat is generated from 100 m^3 of ThermoWood® (table 26). This was calculated using each country's estimates of how much of the heat production comes from wood or wood-based by-products. In the literature, I could not find a percentage of how much energy is produced with wood or wood-derived by-streams in South Africa. That is why recycling rate was used to describe the heat generation from wood or wood-based products in South Africa.

Table 26. Energy production from wood or wood-based products and how much energy can be produced from 100 m^3 of Lunawood's ThermoWood®.

	Share of wood or wood-based products that are burned as in primary energy [%]	**Reference**	**Energy from 100 m^3 of ThermoWood® [MWh]**
Germany	65.3	Umwelt Bundesamt, 2022 and FNR, 2020	52.2
UK	24	UK Energy	19.2
USA	2.1	EIA, 2022	1.68
South Africa	27	Waste report SA, 2018	21.6

Primary energy production from wood or wood-based products values were used to calculate how much energy is obtained when 100 m^3 of thermally modified wood Lunawood is used in energy production (table 25). The cubes were converted to MWh using a conversion factor of 0.80 MWh/m_3 (Lauhanen et al.,2014). In Germany, 100 m^3 of ThermoWood® from Lunawood produces 2.7, 31.1 and 2.4 times more energy than the UK, USA and South Africa, respectively. Almost the same amount of energy can be produced in the UK and South Africa. The share of USA wood in energy production is very small (2.1 %), so 100 m^3 of thermally modified wood from Lunawood produces only 1.68 MWh of energy (table 23). It can be assumed that energy produced with wood or wood-based products reduces the need for other energy production methods, and thus reduces greenhouse gases at the system level.

7.6 Comparison of carbon footprint assessment data of tropical hardwood, competitors of Lunawood and Lunawood's ThermoWood®

The carbon footprints of thermally modified wood calculated in this work using cradle-to-gate approach have been compared with the carbon footprint values found in the literature. To find life cycle assessment data about tropical wood was challenging. Ratnasingam et al. (2015) have evaluated the carbon footprint of Light Red Meranti and Dark Red Meranti tropical trees growing in Malaysia with a gate-to-gate life cycle assessment. The carbon footprints of Accoya (Accoya® wood, 2012) and Kebony (Sustainability report, 2022) were based on a cradle-to-gate approach. The cradle-to-grave life cycle assessments were not found. In this study, the carbon footprint of the production was calculated in such a way that the carbon footprint of both mills of the thermally modified wood manufacturer was calculated separately for the thermally modified wood (thermotimber) and the agreed planed products, after which the average carbon footprint weighted by the amount of production was calculated in relation to the selected markets. Therefore, table 27 shows the carbon footprint range (minimum and maximum value) of Lunawood's thermally modified wood and planed thermally modified wood. The table shows a comparison between different carbon footprint calculations of how much 1 m^3 binds carbon dioxide from the air compared to the greenhouse gas emissions of each producer's product.

Table 27. Comparison of carbon footprint among different actors and CO_2 storage in relation to their carbon footprint.

Producer and LCA approach	**Carbon footprint kg CO_2 eq/m^3**	**Ratio, how much one m^3 stores CO_2 from air compared to the carbon footprint of presented approach***	**Reference**
Lunawood (**cradle-to-gate**)	117	5,41	EPD nro RTS 180 22
Lunawood's thermotimber (**cradle-to-grave**)	225 – 396**	2,33 – 0.89**	This study
Lunawood's, planed (**cradle-to-grave**)	247 – 419**	2,04 – 0.79**	This study
Light Red Meranti (gate-to-gate)	211	2,55	Ratnasingam et al., 2015
Dark Red Meranti (gate-to-gate)	337	1,23	Ratnasingam et al., 2015
Accoya (cradle-to-gate) pine from Scandinavia	140	4,36	Accoya® wood, 2012
Accoya (cradle-to-gate) *Radiata pine from New Zeeland*	342	1,19	Accoya® wood, 2012
Kebony (cradle-to-gate)	353	1,12	Sustainability report, 2022

* Wood binds 750 kg of CO_2/m^3, which has been used in this comparison (Puuinfo).

** These calculations do not take into account that the carbon storage is lost when the wood is burned at the end of its life cycle

Lunawood's cradle-to-gate carbon footprint is 117 kg CO_2 eq/m^3. This is smaller than the carbon footprint of Accoya and Kebony's cradle-to-gate approach, which takes into account the greenhouse gas emissions of the raw material procurement, production, average transportation and disposal phases (RTS 180_22). Lunawood's carbon footprint is also smaller than the tropical hardwoods Light Red Meranti and Dark Red Meranti, whose carbon footprint is calculated with a gate-to-gate approach (Ratnasingam et al., 2015). In this case, emissions caused by harvesting are not taken into account in the calculation. Compared to the carbon footprint of Lunawood's production, Lunawood's thermally modified wood binds more than five times the amount of carbon dioxide from the air, when it is assumed that the wood binds 750 kg of CO_2/m^3 (Puuinfo). Accoya binds more than four times the amount if Scandinavian softwood is used (Accoya® wood, 2012). If they use Radiata pine from New Zeeland (Accoya® wood, 2012), then their product only binds 1.2 times more carbon dioxide from the air. Kebony binds around 1.1. times carbon dioxide from the air (Sustainability report, 2022). The tropical hardwoods Light Red Meranti and Dark Red Meranti bind 2.6 and 1.2 times more carbon dioxide from the air, respectively. According to this study, the cradle-to-grave carbon footprint of Lunawood's thermally modified wood and planed thermally modified wood is 225 – 396 kg CO_2 eq/m^3 and 247 – 419 kg CO_2 eq/m^3, respectively. This assessment has taken into account harvesting, producing, transportation in Finland and up to enduser in different market areas, use phase, recycling and disposal. Therefore, Luanwood's thermally modified wood and planed thermally modified wood bind 0.89 - 2.33 and 0.79 - 2.04 times carbon dioxide, respectively.

8 Discussion

In this work, the calculated carbon footprints of thermally modified wood and planed thermally modified wood using the cradle-to-gate approach have been compared to the carbon footprints of tropical hardwood found in the literature (Ratnasingam et al., 2015) and to the carbon footprints of products of competitors of Lunawood. It was impossible to find other than climate impacts categories to compare. For this reason, the environmental effects are evaluated using global warming potential (GWP). In this work, Lunawood's competitors are Accoya (Accoya® wood, 2012) and Kebony (Kebony, 2022) chemically treated wood, so their production method is not the same, but they compete for the same customers as Lunawood.

8.1 Safeguarding biodiversity in Finland

The Finnish forests are not harvested more than their grow. This is to ensure the adequacy of the carbon sinks. On the other hand, decaying trees are left in the forest, thus safeguarding the diversity of the forest. The drainage of nutrients into water areas is protected by protective zones. Felling is carried out in accordance with the forest management plan. (Metsä, 2020).

It is noted that Finland's forest act is the oldest in the world, and it requires sustainable forest management from forest owners (Metsäteollisuus ry (c), 2022). In addition, PEFC (PEFC, 2019) and FSC (FSC, 2022) certifications require the above-mentioned measures to safeguard biodiversity, mitigate climate change and secure nutrient recycling. According to the PEFC certificate, a total of 10 trees/ha will be saved as retention and decayed trees (PEFC). FSC certified emphasizes that dead trees with a diameter of over 10 cm should be left at 20 pieces/ha. Retention trees, more than 20 cm in diameter and more than 15 cm in northern Finland must be extended to 10 per hectare (FSC). Both certificates upgrade work has begun.

However, Kuuluvainen et al. (2019) states that the protection for biodiversity in Finland is not at a sufficient level. The impact assessment of Finland's biodiversity strategy and action plan also states that the actions taken to protect biodiversity have not been sufficiently effective (Auvinen et al., 2020). For example, between 2013 and 2017, only 1.2 % of stand volume was retained in living retention trees in the private forests (Kuuluvainen et al. 2019). More than 50 % of trees should be left as retention trees when thinning and final felling is in place (Work et al., 2010). In this case, the composition of the forest is the same after five years when compared to uncut stands. Very low levels of retention trees are not able to maintain biodiversity (Work et al., 2010). When only few retention trees or small retention groups of 5 – 10 small-sized trees are left during harvesting major ecological problems are faced because this is not enough to maintain habitat quality (Kuuluvainen et al. 2019). In order to protect boreal biodiversity and comply with international agreements, we need to consider impacts on biodiversity in forest plans and evaluation of forest management strategies (Pohjamies et al., 2017). In order to protect biodiversity, it is necessary to find the most cost-effective solutions and methods to implement them, as the costs can be high (Mönkkönen et al., 2011).

A new biodiversity strategy is currently being prepared, as Finland's biodiversity is deteriorating. If the loss of diversity is measured by the number of endangered species, then the decline has even accelerated. The aim of the new biodiversity strategy is to stop the decline in biodiversity and revitalize situation by 2030. Finland's new strategy will been also connected to international agreement and EU's biodiversity strategy (Ministry of the Environment, 2022). For example, in 1994 Finland ratified the 1992 Convention on Biological Diversity in Rio de Janeiro. The agreement points out that biodiversity has declined, that its protection requires funding, and that the conservation and sustainable use of biological diversity is crucial to meeting the food, health and other needs of the world's growing population (Convention on Biological Diversity, 1994).

8.2 Sustainability awareness raising in companies

Sustainability is constantly being developed in many companies. At the same time, it is being considered how the various aspects of sustainability can be brought out in a communicative way. Husgafvel (2021, Part 1) emphasizes that social sustainability handprints must be developed all the time. Development work must be creative and multidimensional, taking into account the interfaces between society and the environment. Change acts as a driver of action. At Lunawood, sustainability and its importance have been emphasized to all employees. Everyone must contribute to the implementation of sustainability. This does not happen in an instant but requires long-term awareness and a willingness to change. However, the focus of social sustainability is on people and their relationship with the environment. At Lunawood, the change has been driven by the entire management team and Board of Directors. The sustainability framework has needed a change in mindset at the company. Changes in thinking and structures promote social sustainability at every level of the organization (Husgafvel, 2021, Part 1). For change to be visible, it must be measured in some way. This may require work to develop new indicators (Husgafvel, 2021, Part 1). This work helps the company think about new indicators for sustainability that can be used in marketing and communication.

8.3 Data collection for this work

There was information in the literature that could be used to calculate the carbon footprint of ThermoWood®, but data was challenging to find and very time-consuming. Care also had to be taken with the information so that the units were the same or could be converted to the same units. Many carbon footprint calculations for the wood industry have been made using the cradle-to-gate approach, such as Accoya (Sustainability report 2021, 2022) and Kebony (Sustainability report 2022) or the tropical hardwood Light Red Meranti (*Shorea spp.)* and Dark Red Meranti (*Shorea spp.*) LCA (Ratnasingam et al., 2015) a gate-to-gate approach was used. In this study, we went even further and calculated the carbon footprint of Lunawood's ThermoWood® using a cradle-to-grave approach, where carbon dioxide emissions during use phase in selected countries were also taken into account by comparing the lifespan of the product and the square meters used. The boundaries and approaches of the different studies are different, so the results are also different, and therefore not necessarily comparable.

8.4 Scope of the work

The carbon footprint calculation does not take into account CO_2 emissions from buildings, investments or land usage. No data were found for other environmental indicators such as acidification and eutrophication. That's why I researched only global warming potential (GWP). There was challenging in finding initial data for some parts of the life cycle.

8.5 Allocation procedures

Two mass-allocations were made because co-products were generated in the ThermoWood® process. The share of thermowood fiber emissions generated during planing was divided in proportion to how much of the thermowood fiber is made into pellets and how much is used to make the biocomposite. Based on this, the carbon dioxide emission caused by thermowood fiber was subtracted from the total carbon footprint of thermally modified wood. To the main products biocomposite and pellets CO_2 emissions were allocated 2.4% and 19.5% respectively. The allocation had to be made because new products are made from the thermowood fiber generated by the planing side stream. The second mass-allocation is related to the biomass for bioenergy. From the carbon dioxide emission of energy production, which is related to the production of wood chips and transportation of biomass, the carbon dioxide emissions related to the sold energy were subtracted. Allocation was necessary here too, because Lunawood did not use all the energy it produced itself, which is used to manufacture other products. The allocation could have been made, for example, in relation to the use of energy used for planing or in relation to the costs of planing. This would require further research, which would clarify, for example, the energy consumption of the devices and allocate the costs more precisely.

8.6 Comparison with other studies

Ratnasingam et al. (2015) investigated the carbon footprint of Malaysian tropical hardwood sawmilling sector production using a gate-to-gate life cycle approach. Using Light Red Meranti and Dark Red Meranti in the sawmilling industry is generally accepted. In Malaysia, their use is justified not so much by environmental considerations but by economic and availability values. They want to bring out more sustainability thinking in wood harvesting with the help of a sustainable forest management scheme, because there is a strong demand for tropical hardwood. This is to ensure that natural forests are cut in a sustainable manner. (Ratnasingam et al., 2015).

The tropical hardwood, Light Red Meranti and Dark Red Meranti, has a large carbon footprint, 211 kg CO_2 eq/m^3 and 337 kg CO_2 eq/m^3, respectively (Ratnasingam et al., 2015) compared to 117 kg CO_2 eq/m^3 which is the carbon footprint of Lunawood's the gradle-to-gate LCA approach (RTS_180_22). This may be due to the fact that during sawing, a lot of tropical hardwood is wasted and the saws are not so efficient (Ratnasingam et al., 2015). It is also possible that the differences of results in different studies may be caused due to the limitations of each LCA's work.

Therefore, the carbon footprint of Lunawood is 45 % and 65 % smaller than Light Red Meranti and Dark Red Meranti, respectively. This shows that GHG emissions of non-tropical woods are less than from tropical woods. However, it must be taken into account that the carbon footprint of tropical wood is calculated using the gate-to-gate approach, and the carbon footprint of Lunawood's Thermowood® uses the cradle-to-grave approach. which researched the life cycle of the production of ThermoWood® more comprehensively, from wood harvesting to the end of life. Figure 25 shows the carbon footprint of different wood producers and what approach has been used.

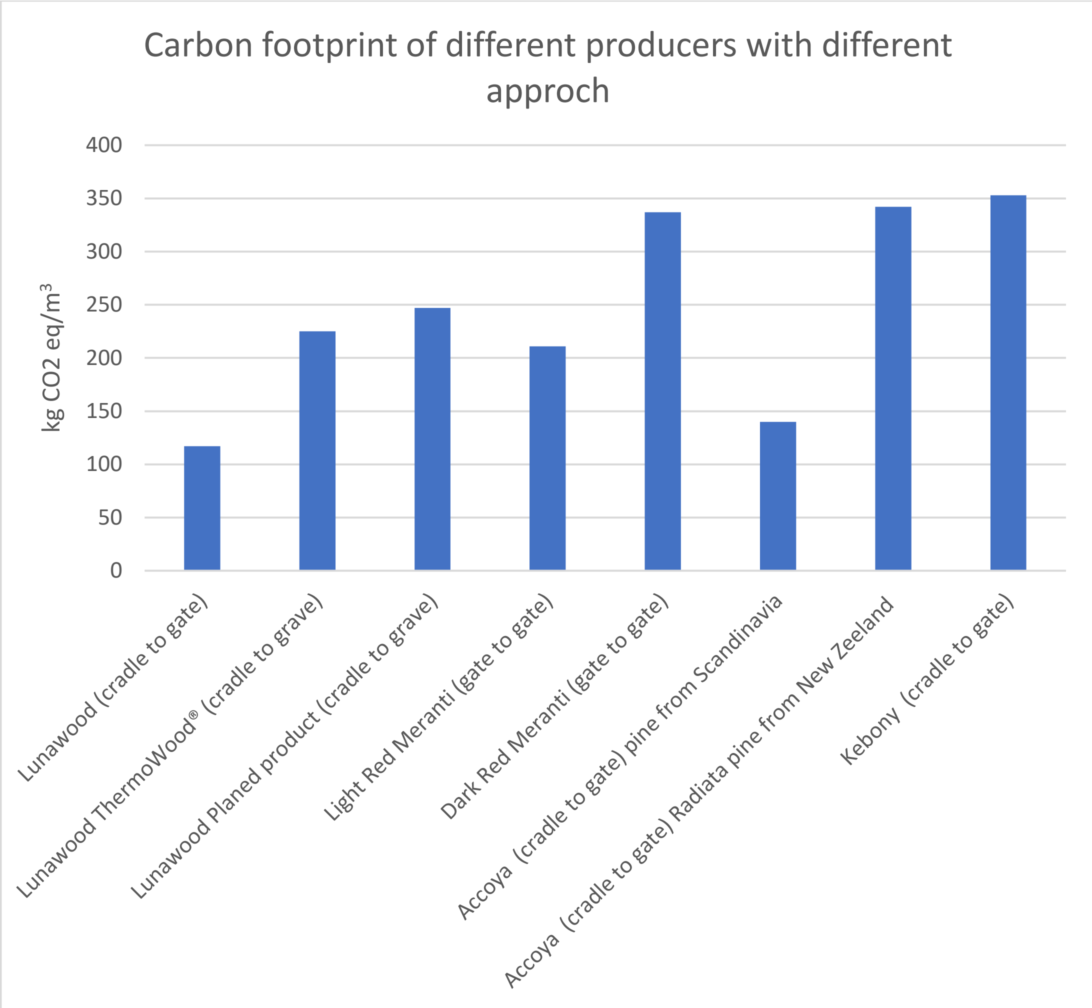


Figure 25. Distribution the carbon footprint of different wood producers and what approach has been used ((RTS_180_22); this study; Ratnasingam et al., 2015; Accoya: Sustainability report 2021, 2022; Kebony: Sustainability report 2021)

Tropical hardwood is a clear competitor to thermal wood. Illegal logging in rainforests causes damage to tropical hardwood's reputation (Sasaki et al., 2016). On the other hand, more attention is constantly being paid to responsible forest management and raw material procurement, in which case this is a clear competitive advantage for responsibly operating companies (Accoya: Sustainability report 2021, 2022; Kebony: Sustainability report 2021; Lunawood: Sustainability report 2021).

Lunawood's closest competitors come from Europe. Thermory has no published carbon footprint. Accoya and Kebony, which chemically treat wood, have published their own carbon footprints, the cradle-to-gate LCA approach. Accoya's carbon footprint is affected by where their raw materials come from. If the raw material comes from Scandinavia, then the carbon footprint of their product is 140 kg CO_2 eq/m^3. If Radiata pine from New Zealand is used as raw material, the carbon footprint is 343 kg CO_2 eq/m^3. Kebony's carbon footprint is 353 kg CO_2 eq/m^3. The carbon footprint of Lunawood in the gradle-to-gate LCA approach is 117 kg CO_2 eq/m^3, which is 16 %, 66 % and 6 7% lower, respectively, compared to Accoya and Kebony.

Based on the results of this study, carbon footprint with the cradle-to-grave approach is lower in the German, UK, and South African markets than Dark Red Meranti gate-to-gate LCA approach and Accoya and Kebony's gradle-to-gate LCA approach carbon footprints. The cradle-to-grave carbon footprint of only the USA market is higher, but it was caused by the USA's large GHG emissions of disposal. It can be said that the Luanwood's ThermoWood® is a climate-friendly product. When comparing the results with other producers, the approaches and methods used in different studies must be taken into account (Accoya: Sustainability report 2021, 2022; Kebony: Sustainability report 2021; Ratnasingam et al., 2015). In this study, lower results were obtained than the competitors before, but the approaches and the wood processing methods are different. This may cause uncertainty in the results.

All the products which were studied in this study and compared are carbon negative compared to the 750 kg CO_2/m^3 (Puuinfo) that wood binds carbon dioxide per cube. A cubic meter of Lunawood's ThermoWood® binds 5.4 times more carbon dioxide from the air than GHG emissions are emitted in production when producing a cubic meter of Lunawood's ThermoWood®. Accoya's Scandinavian pine and Radiata pine and Kebony's product bind carbon dioxide 4.4 times, 1.2 and 1.1 times, respectively. Light Red Meranti and Dark Red Meranti bind carbon dioxide from the air 2.6 and 1.2 times, respectively. Of these, Lunawood's ThermoWood® is the most carbon-negative and climate-positive product. If these are compared to Lunawood's thermotimber exported to different markets, then thermotimber binds carbon 0.89 – 2.33 times, and planed ThermoWood® 0.79 – 2.04 times more.

On the other hand, the choice of building materials is also of great importance. Globally, the construction industry is responsible for 39 % of the world's CO_2 emissions, which includes energy-related CO_2 emissions and construction industry CO_2 emissions (Global Alliance for Buildings and Construction, 2019). Of Finland's total emissions, the construction industry is responsible for 30 % of GHG emissions. 65% of the emissions from construction activities come from building materials (Rantanen, 2020).

When comparing the carbon footprint of Lunawood's ThermoWood® 117 kg CO_2 eq/m^3 gradle-to-gate approach and the carbon footprint of Lunawood for selected market areas 247 – 419 kg CO_2 eq/m^3 with cradle-to-grave approach to hot-formed steel sheet 5731 kg CO_2 eq/m^3 (Koskela, et al. 2011) or for ready-mixed concrete 336 kg CO_2 eq/m^3 (Koskela, et al. 2011), it can be seen that Lunawood's carbon footprint is 98% and 65% smaller compared to steel plate and ready-mixed concrete, respectively. These are building materials, but it should be noted that the uses in buildings are different. Lunawood's cradle-to-grave LCA approach calculated carbon footprint is no more than 26% smaller than precast concrete and 96% smaller than steel plate. Concrete is used the most in buildings, then wood and steel (Koskela, et al. 2011). Based on this comparison, wood is a climate-friendly construction and surface material for use in construction and on various surfaces (Koskela, et al. 2011; Viitala, 2021) in terms of sustainability thinking.

8.7 End-of-life stage

In this work evaluated the CO_2 emissions of demolition waste recycling in selected markets. In different countries, the efficiency of recycling is different and the infrastructure enabling recycling and the operating methods vary. The recyclability and utilization of wood was affected by the infrastructure and existing customs and measures in different countries. When the end-of-life phase is investigated, it can be of significant importance in terms of the formation of GHG emissions. In European countries, wood recycling and its utilization worked better than in South Africa and the USA. Waste wood was often used in energy production, in which case the biogenic carbon bound to it is released into the atmosphere. In this work we did not calculate how much the energy produced by wood replaces other energy production at the system level, but it affects the total emissions and will gain you credits for the produced material or energy. This will impact to module D as a material or energy recovery and thus net impact of the product as shown in Figure 1. Module D was out of system boundary (Figure 1.).

If the materials of an end-of-life product cannot be used, then costs and GHG emissions often increase when it has to be disposed of in a landfill. Combustion of the product causes additional costs, even if energy is produced from it, so the GHG emissions caused by combustion must be properly taken care of. The examination of the GHG emissions of the final stage is at least partially based on assumptions or different scenarios. If the life cycle of the product is long, the margin of error can be large.

When the recycling rates of wood and wood-based waste are low, it can be assumed that then wood waste ends up in MSW in larger quantities. The GHG emissions of the disposal phase are indicative, because MSW also includes other organic waste. In the USA, less wood is recycled, so more of it ends up in landfills, along with municipal solid waste. In South Africa, wood is reused and is an important fuel when cooking. For Germany, the results of GHG emission caused by the MSW management of the landfill will change, because with the new EU waste legislation, organic matter can no longer be put in a landfill (Directive 2008/98/EC).

Germany has succeeded in implementing the EU waste hierarchy (EU, Waste prevention and management) by recycling and reducing the amount of waste going to the landfill, because the recycling rate is high (Garcia & Hora, 2017) and greenhouse gas emissions of disposed municipal solid waste management are low (Mühle et al., 2010). The UK recycling rate (UK Gov, 2022) is lower than in Germany, so side streams still go to the landfill that could be recycled. Greenhouse gas emissions from MSW management are five times higher than MSW management emissions in Germany (Mühle et al., 2010). The USA recycling rate is the lowest (EPA, 2021 a), so it can be concluded that there is still work to be done in preventing the generation of waste and promoting the circular economy (EPA, Waste Management Hierarchy). Of the market areas in this study, the USA produces the most greenhouse gases in municipal solid waste management (Nordahl et al., 2020). In South Africa, the recycling rate could be increased (Waste report SA, 2018). Wood is used a lot as fuel, but its processing value could be increased before it is burned. Municipal solid waste management causes the same amount of emissions as the UK (Friedrich, E., 2013).

8.8 Using wood products to reduce CO_2 emissions The effect of the use time of ThermoWood® on the results

GHG emissions during use phase are affected by how long the product is used and in what area. The longer the period of use of ThermoWood®, the lesser emissions are produced per year. The carbon footprint of a planed product and during use is greater than an unplaned product. On the other hand, it was assumed that the service life of ThermoWood® outdoors is longer than indoors. Leading that the GHG emission of thermally modified wood used on terraces and facades is lower per m^2. In this work, the GHG emission, which is released from one square meter of planed thermally modified wood per cube (5.26 kg CO_2 eq/m^3/a), was used as the emission during the service life of the gradle-to-grave LCA approach of the thermally modified wood of Lunawood (this study). In all selected market areas, Germany, UK, USA and South Africa, the emissions during the service life of Lunawood's ThermoWood® are increasing as the number of square meters increases and decreasing in proportion to the used service life.

Viitala (2021) analyzed the total carbon footprint of buildings, where the largest emissions were from the manufacture of building products and materials (42%) and energy consumption during the building's operational phase (47%). The total carbon footprint of the building was 16.5 kg CO_2 eq/m^2/a. For wood products, the carbon footprint was 0.4 kg CO_2 eq/m^2/a (Viitala, 2021). Therefore, it can be assumed that wood products could act as a carbon sink and thus be used to compensate for the building's carbon footprint.

The carbon dioxide emissions of thermotimber and planed ThermoWood® used outdoors are lower than ThermoWood® used indoors/m^2. This is due to the fact that thermally modified wood is used for longer in outdoor use. In addition to the preference of the end user, the use of wood in interiors is influenced by interior design trends. Wood is currently considered a very trendy and responsible material (Decorpot; NowyStyl). Lunawood's products have been found to be ecological and environmentally friendly for use indoors and outdoors as decorative surface applications. Also, there are produced from certified Nordic raw materials which is an important fact for customers who are buying wooden products (Veisten 2002) and they are willing to pay a premium for certified wooden products (Ozanne & Vlosky, 1997).

8.9 The importance of communication in sustainability communication

The thermally modified wood manufacturer highlights in its sustainability communication that no chemicals have been used in the ThermoWood®, the raw material comes from Finland, the product is durable and it is well designed. Consumers value precisely these properties in sustainable wood products (Holopainen et al., 2014). Communicating sustainability actions is not easy. The consumer must be given sufficient information to support his decision, launching awareness campaigns and environmental education as well as applying greenness as a complementary product attribute would be some of the solutions to attract larger consumer groups (Holopainen et al. 2014). Lunawood has developed its sustainability communication in different communication channels so that the most important thermally modified wood properties are systematically highlighted in communication and marketing (Figure 5, this study). With the help of marketing, the sustainability issues of the entire supply chain of ThermoWood® are brought to the fore, so that consumers have comprehensive information about environmentally friendly ThermoWood®. This not only benefits the environment, but also gives companies opportunities to develop their sustainability communication (Moser, 2016). Consumers of Finnish ThermoWood® are often aware of the ecological and environmentally friendly properties of ThermoWood® make their purchase decisions according to these properties. For consumers who are concerned about their environment, buying environmentally friendly and sustainable products gives them the opportunity to transfer their environmental concerns to activities that benefit the environment, i.e. by buying environmentally friendly products they mirror these environmental attitudes in their self-reported purchasing behavior. Such shopping behavior is called "green" buying behavior (Moser, 2016). Consumers who choose sustainable produced and environmentally friendly products, such as Finnish ThermoWood®, also have a willingness to pay (WTP) more for such a product (Moser, 2016). More expensive products have their own brand, which in itself already costs money, but the consumer is primarily guided by the product's quality and related features, not the brand (Achabou & Dekhili, 2013)

8.10 Potential actions to reduce carbon footprint of ThermoWood®

The carbon footprint of the ThermoWood® manufacturer could be reduced by changing fossil fuels to renewable fuels. Electricity could be bought as a green electricity. Solar panels could be placed on the roofs of mills for their own use. Internal logistics emissions can be reduced by rationalizing the use of forklifts. Combustion engine forklifts can also be changed to electric forklifts. At the ThermoWood® manufacturer's mills, efforts have been made to improve energy efficiency, which has reduced CO_2 emissions. Carbon dioxide emissions from transport could be reduced by requiring logistics companies to use renewable fuels. In the end, the emissions from transporting products can be compensated with the help of compensation mechanisms of logistics companies. The entire supply chain is needed to reduce transport emissions. Lunawood’s customers could also use renewable fuels when transporting products to the end user. It would be good to find out how ThermoWood® itself could be used as a compensation tool in various construction projects.

9 Conclusion

Lunawood’s thermally modified wood and planed thermally modified wood can be considered as a carbon storage as long as the thermally modified wood is burned at the end-of- life stage. More carbon can be stored to these products than is released along their life cycle. In this work Thermowood®’s carbon footprint is calculated using the cradle-to-grave LCA approach.

ThermoWood® is a carbon-negative product because it binds more carbon from the atmosphere than is generated in its production. This is why it is an interesting building material to be used in different surfaces in buildings from the point of view of low-carbon construction.

Thermally modified wood could be used as a compensation tool for the carbon dioxide emissions of the construction site which would require further research. On the other hand, developing a service concept in which the used product would be taken back might increase recycling and reusage. In that way carbon store can be upkept. Only as a last option would thermally modified wood be used for energy recovery. Such a model could be scaled to be operational globally. Continuous research and responsible thinking from multiple perspectives are needed all the time so that a company can say that its own products are sustainable products.

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Appendix 1. Confidential material

The content of this appendix may be accessed by contacting Lunawood.